

FABIANE DE FÁTIMA MACIEL

LIFE CYCLE ASSESSMENT OF THE BRAZILIAN EGG INDUSTRY

Thesis submitted to the Agricultural Engineering Graduate Program of the Universidade Federal de Viçosa in partial fulfillment of the requirements for the degree of Doctor Scientiae.

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To God, who girds me with strength and makes my way perfect. (Psalm 18:33)

I OFFER!

To the eternal Professor Dr. Richard Stephen Gates (In memoriam).

For him and to him...

I DEDICATE!

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*“Faith is to believe what you do not see;
the reward of this faith is to see what you believe.”*

(Saint Augustine)

BIOGRAPHY

FABIANE DE FÁTIMA MACIEL, daughter of Benedito da Costa Maciel and Maria Aparecida Maciel, was born in the city of Ouro Fino – Minas Gerais, Brazil, on September 5th, 1988.

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ABSTRACT

MACIEL, Fabiane de Fátima, D.Sc., Universidade Federal de Viçosa, February, 2024. **Life Cycle Assessment of the Brazilian Egg Industry.** Advisors: Richard Stephen Gates. Co-advisors: Ilda de Fátima Ferreira Tinôco, Fernanda Campos de Sousa, Natalia dos Santos Renato e Nathan Pelletier.

Brazil stands out as one of the world's main producers of animal protein, ranking sixth in global egg production. However, production growth, along with environmental impacts, pose a potential threat to the sustainability of the food system. Methods for evaluating and quantifying the environmental impacts generated by Brazilian egg production remain scarce, lacking current reports on comparative effects or guiding standards. Therefore, new production systems are being implemented slowly, as the adoption of new systems can impact the price of the product and make it less accessible to the consumer. With the aim of supporting and promoting improvements related to sustainability in the Brazilian egg industry, this study aims to carry out an assessment of the life cycle, from the cradle to the farm gate, in accordance with ISO 14040 and 14044 standards, for the intensive production of eggs in cages. Egg production-related emissions results were 65.06 kg SO₂ eq., 27.74 kg N eq., 3,086.71 kg CO₂ eq., 75,152.66 CTUe, 2.75E-05 CFC-11 eq.; 1,0044.68 kg MJ eq. per ton of eggs produced. When considering the results of CO₂ emissions eq. in international life cycle assessments in egg production, the values represent 1.4 to 5.58 kg of CO₂ eq. per kg of egg produced. Countries such as Czech Republic, Canada, USA, UK, Australia and Sweden have smaller carbon footprints when compared to Brazilian production. While Mexico, Spain and the Netherlands represent larger footprints than Brazilian egg production. When comparing the results of this study with the values of the environmental impacts of Brazilian agro-industrial productions, egg production represents impacts relatively close to the average impacts of broiler and swine production. To compose this work, four articles were developed. The first two articles dealt with the state of the art in approaching the topics: I) life cycle thinking as a qualitative model and life cycle assessment as a quantitative scientific method; II) assessment of the life cycle of egg production, focusing on international studies, but aimed at assessing the life cycle of the Brazilian egg industry. The last two scientific articles address: III) the modeling of the composting area included as part of the life cycle inventory; IV) the final assessment of all environmental impacts related to the production of eggs and related products in the intensive cage system. As this is the first assessment of the life cycle of the Brazilian egg industry, the results presented may serve as a comparative reference for future studies and data analyzes in different egg production systems

in Brazil. These findings provide a basis for continued efforts to improve sustainability practices in the industry and offer valuable information for stakeholders seeking to implement effective interventions for a more sustainable egg production system in the country.

Keywords: Agricultural sector. Category of impacts. Emissions. Environmental impacts. Inventory analysis. Productive chain. Sustainability.

RESUMO

MACIEL, Fabiane de Fátima, D.Sc., Universidade Federal de Viçosa, fevereiro de 2024. **Avaliação do Ciclo de Vida da Indústria Brasileira de Ovos.** Orientadores: Richard Stephen Gates. Coorientadores: Ilda de Fátima Ferreira Tinôco, Fernanda Campos de Sousa, Natalia dos Santos Renato e Nathan Pelletier.

O Brasil se destaca como um dos principais produtores mundiais de proteína animal, ocupando o sexto lugar na produção global de ovos. No entanto, o crescimento da produção, juntamente com os impactos ambientais, representam uma ameaça potencial à sustentabilidade do sistema alimentar. Os métodos para avaliar e quantificar os impactos ambientais gerados pela produção brasileira de ovos continuam escassos, carecendo de relatórios atuais sobre efeitos comparativos ou padrões orientadores. Desta forma, novos sistemas de produção estão sendo implantados lentamente, uma vez que a adoção de novos sistemas podem impactar no preço do produto e torná-lo menos acessível ao consumidor. A fim de apoiar e promover melhorias relacionadas a sustentabilidade na indústria brasileira de ovos, este estudo tem como objetivo avaliar o ciclo de vida, do berço ao portão da granja, em conformidade com a ISO 14040 e 14044, do sistema intensivo de produção de ovos em gaiolas. Os resultados das emissões referentes a produção de ovos foram de 65.06 kg SO₂ eq., 27.74 kg N eq., 3086.71 kg CO₂ eq., 75152.66 CTUe, 2.75E-05 CFC-11 eq., 10044.68 kg MJ eq. por tonelada de ovos produzidos. Ao considerar os resultados das emissões CO₂ eq. nas avaliações internacionais de ciclo de vida na produção de ovos, os valores representam 1.4 a 5.58 kg de CO₂ eq. por kg de ovo produzido. Os países como República Tcheca, Canadá, EUA, Reino Unido, Austrália e Suécia representam pegadas de carbono menores quando comparados a produção brasileira. Enquanto México, Espanha e Holanda representam pegadas maiores que a produção de ovos brasileira. Ao comparar os resultados deste estudo aos valores dos impactos ambientais das produções agroindustriais brasileiras, a produção de ovos representa impactos relativamente próximos a média dos impactos das produções de frango de corte e suínos. Para compor este trabalho, foram desenvolvidos quatro artigos. Os dois primeiros artigos trataram do estado da arte na abordagem dos temas: I) o pensamento do ciclo de vida como modelo qualitativo e a avaliação do ciclo de vida como um método científico quantitativo; II) avaliação do ciclo de vida da produção de ovos, com foco em estudos internacionais, porém voltados para a avaliação do ciclo de vida da indústria brasileira de ovos. Os dois últimos artigos científicos abordam: III) a modelagem da área da compostagem inserida como parte do inventário do ciclo de vida; IV) a avaliação final de todos os impactos ambientais relacionados à produção de ovos e produtos relacionados, no

sistema intensivo em gaiolas. Por ser a primeira avaliação do ciclo de vida da indústria brasileira de ovos, os resultados apresentados poderão servir como referência comparativa para estudos futuros e análises de dados em diferentes sistemas de produção de ovos no Brasil. Estas conclusões fornecem uma base para os esforços contínuos para melhorar as práticas de sustentabilidade na indústria e oferecem informações valiosas para as partes interessadas que procuram implementar intervenções eficazes para um sistema de produção de ovos mais sustentável no país.

Palavras-chave: Análise de inventário. Cadeia produtiva. Categoria de impactos. Emissões. Impactos ambientais. Setor agrícola. Sustentabilidade.

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LIST OF ACRONYMS AND ABBREVIATIONS

ABNT	Brazilian Association of Technical Standards.
ABPA	Brazilian Association of Animal Protein.
ANVISA	National Health Surveillance Agency.
ASAE	American Society of Agricultural Engineers.
C/N	Carbon/Nitrogen.
CAPES	Coordination of Superior Level Staff Improvement.
CEPEA	Center for Advanced Studies in Applied Economics
CF	Carbon Footprint
CFC-11 eq.	Trichlorofluoromethane equivalent
CH ₄	Methane
CNPq	National Council for Scientific and Technological Development
CO ₂ eq.	Carbon dioxide equivalent
CO ₂	Carbon dioxide
CP	Crude protein
CTUe	Comparative toxic unit equivalent
CW	Central-western region
DDGs	Dried distillers' grains
DEQ's	Oregon Department of Environmental Quality
EF	Ecological Footprinting
E-LCA	Life Cycle Environmental Assessment
EMBRAPA	Brazilian Agricultural Research Corporation
EPA	Environmental Protection Agency
EU	Energy Use
FAO	Food and Agriculture Organization
FAPEMIG	Minas Gerais Research Support Foundation, Brazil
FCR	Feed Conversion Ratio
FU	functional unit
GHG	Greenhouse Gas
GWP	Global Warming Potential
HPA	Hotspot Analysis
IBGE	Livestock Production Statistics Report
IBICT	Brazilian Institute of Information in Science and Technology

IFSULDEMINAS	Federal Institute of Education, Science, and Technology of the South of Minas Gerais
INMETRO	National Institute of Metrology, Quality and Technology
IPCC	Intergovernmental Panel on Climate Change
IPPU	Industrial Processes and Product Use
ISO	International Organization for Standardization
ISU	Iowa State University
LCA	Life Cycle Assessment
LCC	Life Cycle Costing
LCDI	Life Cycle Data Interpretation
LCF	Low-Cost Feed
LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Assessment
LCInitiative	Life Cycle Initiative
LCM	Life Cycle Management
LCSA	Life Cycle Sustainability Assessment
LCT	Life Cycle Thinking
LU	Land Use
LULUCF	Land Use, Land-Use Change, and Forestry
LUR	Land Use Ratio
MAPA	Ministry of Agriculture and Livestock
MCTI	Ministry of Science, Technology, and Innovations
ME	Metabolizable Energy
MJ eq.	Megajoule equivalent
MOS	Mannan Oligosaccharides
N eq.	Nitrogen equivalent
N	Nitrogen
N ₂ O	Nitrous oxide
NBR	Brazilian Technical Standard
Nex	Average N excretion
NH ₃	Ammonia
NO ₃	Nitrate
NO _x	Nitric oxide
Nrate	Standard N excretion rate

Nt	Total nitrogen
NUE	Nitrogen Use Efficiency
NZE	Net Zero Energy
P	Phosphorus
SBM	Soybean Meal
SD	Sustainable Development
SETAC	Society for Environmental Toxicology and Chemistry
SICV Brazil	National Bank of Life Cycle Inventories
S-LCA	Social Life Cycle Assessment
SO	Southern region
SO ₂ eq.	Sulfur dioxide equivalent
SRI	Sustainable Recycling Industries
TAM	Typical animal mass
UBC	University of British Columbia
UFV	Federal University of Viçosa
UNEP	United Nations Environment Program
VS	Mean excretion of volatile solids
VSrate	Standard SV excretion rate
WF	Water Footprint

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GENERAL INTRODUCTION

Brazil is considered a country with expressive participation in the market for animal protein, holding prominent positions in the global rankings. In 2022, the country was the second-largest producer of beef and chicken, ranking first in exports for both products [1,2]. Additionally, it also was the fourth-largest producer of swine and ranked fourth in the export market [1]. Brazil is also the sixth-largest producer of eggs, with a production of over 52.06 billion units this year [3]. According to the Brazilian Animal Protein Association (ABPA) [1], 99.6% of Brazilian egg production is destined for the domestic market, with only 0.44% destined for the international market, with an expectation of growth in the export market in the coming years. Despite the export market for eggs (57% in natural state

and 43% processed eggs) representing less than 1% of the national production, Brazilian eggs are present in the tables of consumers in 83 countries, distributed across the Middle East (64.41% of the import market), Americas (16.42%), Asia (14.49%), Africa (1.42%), Oceania (1.37%), European Union (1.16%), and Europe Extra-EU (0.46%) [1,3].

The projected increases in demand for animal-derived products, associated with the environmental impacts, pose a potential risk to the sustainability of the food system (from production, processing, and distribution of food), which consequently accounts for 21% to 37% of global greenhouse gas (GHG) emissions [4]. According to the Food and Agriculture Organization (FAO) [5] and the Intergovernmental Panel on Climate Change (IPCC) [6], between 1990 and 2019, global emissions from these systems increased by approximately 16%, with prospects of further growth due to increased demand. In this way, it becomes necessary to identify and disseminate the best sustainability management practices to achieve reductions in production impacts.

Sustainability in livestock production is also related to food security, work safety, economic accessibility, and animal welfare [7]. Thus., it is considered a challenge for the animal production system, especially activities related to the egg industry, to balance all these environmental factors and meet current production demands [7,8].

The predominant egg production system in Brazil is the intensive system in cages with open or semi-open laying houses. This system accounts for 95% of the national egg production. Within this production system, there are two predominant types of facilities, differentiated by the arrangement of the cages: the pyramid or Californian model and the vertical model [9]. Extensive or alternative systems such as Cage-Free, Free-Range, Organic, and Colonial "backyard" in Brazil represent an estimated 5% of production, not being effectively quantified

by production statistical agencies [9,10]. These systems have specific characteristics related to the conditioning and housing of laying hens, feeding (in the case of organic production), and the cost of the produced egg [11].

In Brazil, methods for assessing and quantifying the environmental impacts generated by egg production are still scarce. There are currently no records for comparative effects or even guidelines for improvements in production. In this way, new production systems are being implemented slowly, as the adoption of new systems can impact the price of the product and make it less accessible to consumers [12].

The Life Cycle Assessment (LCA) is considered a leading methodology for evaluating the environmental performance of a production system [13]. LCA is an internationally standardized method, and its application is governed by ISO 14040-14044 standards [14,15]. LCA is used to assess the potential environmental and human health impacts related to products and services over their life cycle, starting from raw materials extraction and including all production processes, transportation, manufacturing, use, and end-of-life treatment [16]. It is noteworthy that LCA applications allow to estimate the potential environmental impacts of a system throughout its entire life cycle, quantifying probable emissions produced and resources consumed within current scientific and data limitations, as well as identifying "hotspots" within the supply chain, which may be priority targets for sustainability improvement efforts [17]. Hence, the environmental impacts calculated through LCA should not be interpreted as absolute values but rather as relative within the scope of the study [18].

As a calculation tool, the open-source software for Life Cycle Assessment OpenLCA, version 2.0 [19], along with the Ecoinvent database, version 3.9.1, share a set of flows, called product flows, elementary flows (taken from the environment without prior human transformation), and waste flows [20]. Processes are created from these flows, which are listed and quantified as inputs and outputs (through inventory data), consequently allowing the creation of a whole product system. By creating a product system, it is possible to calculate the impacts generated through the desired impact evaluation method [21].

LCA has been applied to many egg production systems worldwide, in countries such as the Czech Republic [22], Canada [23–26], Mexico [27], USA [28], Spain [29], UK [30,31], Australia [32], Netherlands [33], Sweden [34], among others. These studies consistently identified feed production and manure management practices as the main contributors to the environmental impacts of the egg production chain. In this way, the results of these studies can provide relevant information and interventions for improvement in favor of egg production sustainability.

In order to support and promote improvements related to sustainability in the Brazilian egg industry, this study aims to conduct a life cycle assessment from cradle to farm gate, following ISO 14040 and 14044 standards [14,15], for the intensive system of egg production in cages. More specifically, this study aims to quantify the use of resources and emissions attributable to the evaluated production system, as well as specific production inputs. The essay looks to identify the potential for mitigation and specific interventions to improve resource use efficiency and reduce emissions from Brazilian egg production. In the future, this developed baseline model could be used to support additional analyses and comparisons investigating strategies for environmental impact mitigation, as well as improvement plans in the production system, such as the implementation of new technologies, optimization of natural resources, waste valorization, among other strategies [35–38].

To compose this thesis, four articles were developed. The first two articles addressed the state of the art in the following topics: I) life cycle thinking as a qualitative model and life cycle assessment as a quantitative scientific method; II) life cycle assessment of egg production, focusing on international studies, however, aimed at assessing the life cycle of the Brazilian egg industry. The last two scientific articles addressed: III) modeling of the composting area included as part of the life cycle inventory; IV) the final evaluation of all environmental impacts related to egg production and related products in the intensive cage system.

The first literature review article, entitled "LIFE CYCLE THINKING AND ITS IMPORTANCE IN THE CONTEXT OF SUSTAINABILITY MANAGEMENT: REVIEW," approaches the concepts and tools of life cycle thinking, making it possible to define the stages of a product's life cycle, structure sustainable ideas, and implement innovative strategies and solutions in production.

The second literature review article, titled "LIFE CYCLE ASSESSMENT PROJECT FOR THE BRAZILIAN EGG INDUSTRY," is a literature review on the LCA methodology through international life cycle assessments of egg production. This review presents the concept and the accounting structure of LCA, through Life Cycle Inventory (LCI) and Life Cycle Impact Assessment (LCIA), to quantify the environmental performance of production and identify areas for future improvements, thus promoting the environmental footprint of the Brazilian egg industry.

The third scientific article, entitled "MANAGEMENT OF LAYING HEN MANURE IN INTENSIVE COMPOSTING WITH WINDROWS: MODELING EMISSIONS OF N, P, AND CH₄," describes how the values related to gas emissions from the composting area were calculated using IPCC guidelines for national greenhouse gas inventories. The results were

calculated considering the annual production and the functional unit of 1000 units of pullets produced in rearing facilities and one ton of eggs produced in laying facilities.

The fourth and final scientific article, entitled "ENVIRONMENTAL IMPACTS OF THE BRAZILIAN EGG INDUSTRY: LIFE CYCLE ASSESSMENT OF THE INTENSIVE CAGE PRODUCTION SYSTEM," addresses the entire life cycle assessment from cradle to farm gate, following ISO 14040 and 14044 standards [14,15], for the intensive egg production system in cages and related products. This assessment includes the quantification of resources and emissions attributable to the evaluated production system, as well as the potential for mitigation and specific interventions. As the first life cycle assessment of the Brazilian egg industry, the presented results can serve as a comparative reference for future studies and data analyses in different egg production systems in Brazil. These conclusions provide a basis for ongoing efforts to improve sustainability practices in the industry and offer valuable insights for stakeholders seeking to implement effective interventions for a more sustainable egg production system in the country.

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Life Cycle Thinking and its importance in the context of sustainability management: Review

Pensamento do Ciclo de Vida e sua importância no contexto da gestão da sustentabilidade: Revisão

Pensamiento del Ciclo de Vida y su importancia en el contexto de la gestión de la sostenibilidad: Revisión

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Abstract

Life Cycle Thinking (LCT) is considered a qualitative study because it describes the environmental impacts of a product or process. This perception allows us to identify the potential effects and resources used, allowing us to structure sustainable ideas, identifying and developing innovative solutions. Establishing the life cycle of a product requires planning and understanding the stages of the production chain, the continuous assessment of processes and their environmental functions, from the extraction of raw materials, transportation, manufacturing process, delivery to the customer and final disposal. Although LCT is considered a philosophy, Life Cycle Assessment (LCA) is a quantitative scientific method that allows you to express this thought. Through life cycle concepts and tools, it becomes possible to define the stages of a product's life cycle, assist decision makers in data analysis and implement sustainability with appropriate strategies and actions. However, the objective of this review is to describe concepts and definitions about LCT and LCA. It is hoped that researchers will be able to guarantee true sustainability in production, which will require careful assessment and multiple considerations based on an in-depth reflection on the product's life cycle.

Keywords: Environment; Environmental management; Sustainable production; Environmental impacts.

Resumo

O Pensamento do Ciclo de Vida (PCV) é considerado um estudo qualitativo por descrever os impactos ambientais de um produto ou processo. Esta percepção permite identificar os potenciais efeitos e recursos utilizados, permitindo estruturar idéias sustentáveis, identificando e desenvolvendo soluções inovadoras. Estabelecer o Ciclo de Vida de um produto requer planejamento e compreensão das etapas da cadeia produtiva,

a avaliação contínua dos processos e suas funções ambientais, desde a extração da matéria-prima, transporte, processo de manufatura, entrega ao cliente e disposição final. Embora o PCV seja considerada uma filosofia, a Avaliação do Ciclo de Vida (ACV) é um método científico quantitativo que permite expressar esse pensamento. Por meio de conceitos e ferramentas de ciclo de vida, torna-se possível definir as etapas do ciclo de vida de um produto, auxiliar os tomadores de decisão na análise de dados e implementar a sustentabilidade com estratégias e ações adequadas. Contudo, o objetivo desta revisão é descrever conceitos e definições sobre PCV e ACV. Espera-se que os investigadores consigam garantir uma verdadeira sustentabilidade na produção, o que exigirá uma avaliação detalhada e múltiplas considerações baseadas numa reflexão aprofundada sobre o ciclo de vida de um produto.

Palavras-chave: Meio Ambiente; Gestão Ambiental; Produção Sustentável; Impactos Ambientais.

Resumen

El pensamiento del ciclo de vida (PCV) se considera un estudio cualitativo porque describe los impactos ambientales de un producto o proceso. Esta percepción le permite identificar los efectos potenciales y los recursos utilizados, permitiéndole estructurar ideas sostenibles, identificando y desarrollando soluciones innovadoras. Establecer el Ciclo de Vida de un producto requiere planificar y comprender las etapas de la cadena productiva, evaluación continua de los procesos y sus funciones ambientales, desde la extracción de la materia prima, el transporte, el proceso de fabricación, la entrega al cliente y la disposición final. Aunque la PCV se considera una filosofía, el Analisis del Ciclo de Vida (ACV) es un método científico cuantitativo que permite expresar este pensamiento. A través de conceptos y herramientas del ciclo de vida, es posible definir las etapas del ciclo de vida de un producto, ayudar a los tomadores de decisiones en el análisis de datos e implementar la sostenibilidad con estrategias y acciones apropiadas. Sin embargo, el objetivo de esta revisión es describir conceptos y definiciones sobre PCV y ACV. Se espera que los investigadores puedan garantizar una verdadera sostenibilidad en la producción, lo que requerirá una evaluación cuidadosa y múltiples consideraciones basadas en una reflexión profunda sobre el ciclo de vida de un producto.

Palabras clave: Medio Ambiente; Gestión Ambiental; Producción Sostenible; Impactos Ambientales.

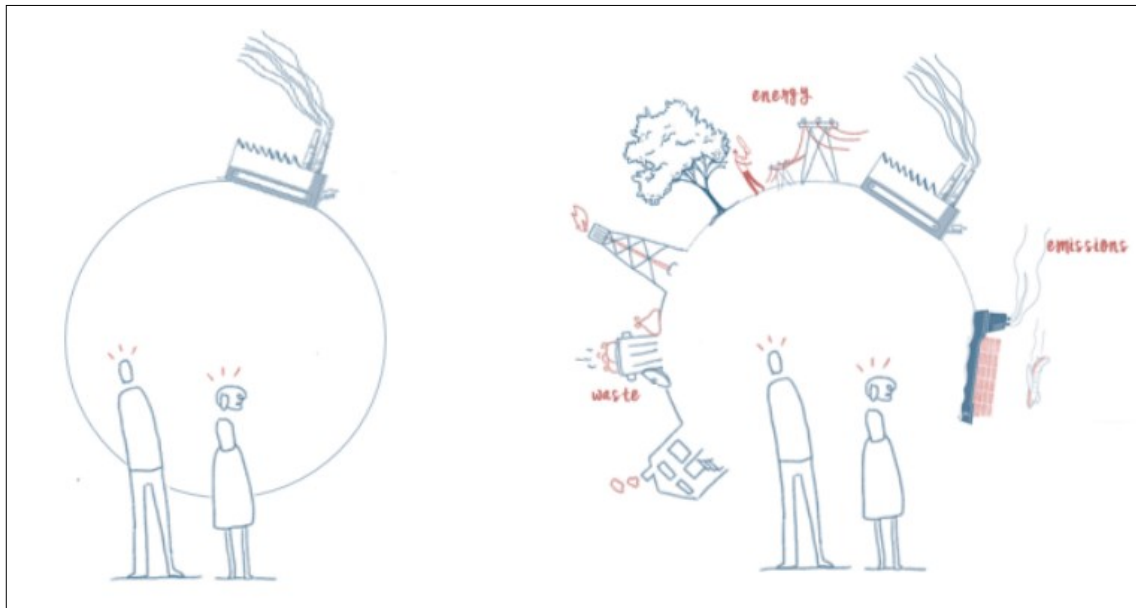
1. Introduction

In the past, when consumers had to choose between two similar products, it was easy to make the decision, just look at the cost and quality benefits and then choose the one that suited them best. Currently, the choices are more difficult. Consumers are motivated to be more aware of the effects and impacts on the environment and local economies (UNEP/SETAC, 2009).

Life Cycle Thinking (LCT) is considered a qualitative study that assesses the environmental impacts of a product or process. This insight allows us to identify the effects and potential resources used throughout its life cycle. Assessments based on this perspective describe different forms of assessment, followed by formalized approaches established in international protocols and scientific literature (MDB, 2014).

The programs and guides developed by the United Nations Environment Program (UNEP), Society for Environmental Toxicology and Chemistry (SETAC) and Life Cycle Initiative (LC Initiative), define LCT as a process that goes beyond the traditional focus (figure 1) on production and manufacturing processes to include the environmental, social, and economic impacts of a product throughout its life cycle. While LCT is considered a philosophy, Life Cycle Assessment (LCA) is a scientific method that allows expressing this thought (UNEP/SETAC, 2012).

Figure 1 - Production and manufacturing processes without and with LCT.



Source: Life Cycle Thinking (LCT, 2021)

In September 2015, the United Nations announced the 17 Sustainable Development Goals, with 169 associated goals to be achieved by 2030. However, for these goals to be achieved, they need to be dated. It becomes impossible to convince leaders to employ sustainability when the goals are unknown, that is when there is no environmental education built. Therefore, to achieve the goals, environmental intelligence is necessary and the LCT is part of this intelligence (Bojarska, J. Zloty, P. Wolf, 2021).

LCT also allows you to structure sustainable ideas, identifying and developing innovative solutions. The compensatory exchanges stand out, which allow avoiding a single metric, generated by situations in which only one polluting agent is considered, by including all other relevant environmental impacts throughout the life cycle (European Commission, 2010).

The principle that using fewer materials is best for promoting sustainability may not always hold true if the full life cycle is not considered. According to a study sponsored by the Oregon Department of Environmental Quality (DEQ's, 2004), concrete forms and double-wall construction provide better thermal insulation, which reduces energy consumption. In this case, the energy reduction due to insulation outweighed the environmental costs of adding materials used in residential construction (MDB, 2014).

The same happens with the analysis of a product with high energy efficiency. The energy used during the use phase will be less than the energy used by products with low energy efficiency. However, realize that a high-efficiency product production will need more materials for its production than any conventional product. In this way, it is possible to conclude that the production will only be sustainable if the impacts generated to produce are smaller than the impacts avoided during the entire phase of use of the product. It emphasizes the existence of several types of relevant impacts besides energy, such as climate change, loss of biodiversity, and adverse social problems (LCT, 2021).

According to LC Initiative (2021) considers the two main categories of Life Cycle approaches: concepts and tools. The definition of "life cycle concepts" is based on the principles that guide and inspire the decision-making process. This conceptual vision defines all stages of the life cycle of a product or process and guides the correct application of

tools, which are implemented by data and information. The tools also assist in decision making through data analysis, which thus implements sustainability, providing appropriate actions to be taken. Therefore, the objective of this review is to describe all the concepts about LCT and the ways to carry out a LCA in a production system. However, this review aims to provide a greater understanding of the system as a whole, its impacts and the complexity of the production system. As a result, it is expected that these evaluation techniques can be used by companies, organizations, academies, NGOs, governments, etc. Considering the need for evaluators with substantial knowledge on how to use, analyze and evaluate the techniques and how to interpret the results.

2. Methodology

As it is a narrative review study, this review offers methodological support for research focused on Life Cycle Thinking in the context of sustainability management. The main guides developed by the United Nations Environment Program (UNEP), Society of Toxicology and Environmental Chemistry (SETAC) and Life Cycle Initiative (LC Initiative), seek to describe concepts and guidelines so that more research can be developed. All bibliographic references selected in this study are part of databases consulted via Google Scholar, CAPES Periodicals, among others. The main question of this review tends to guide and integrate Life Cycle Thinking and Life Cycle Assessment in order to promote real sustainability in a production system.

2.1 Life cycle concepts

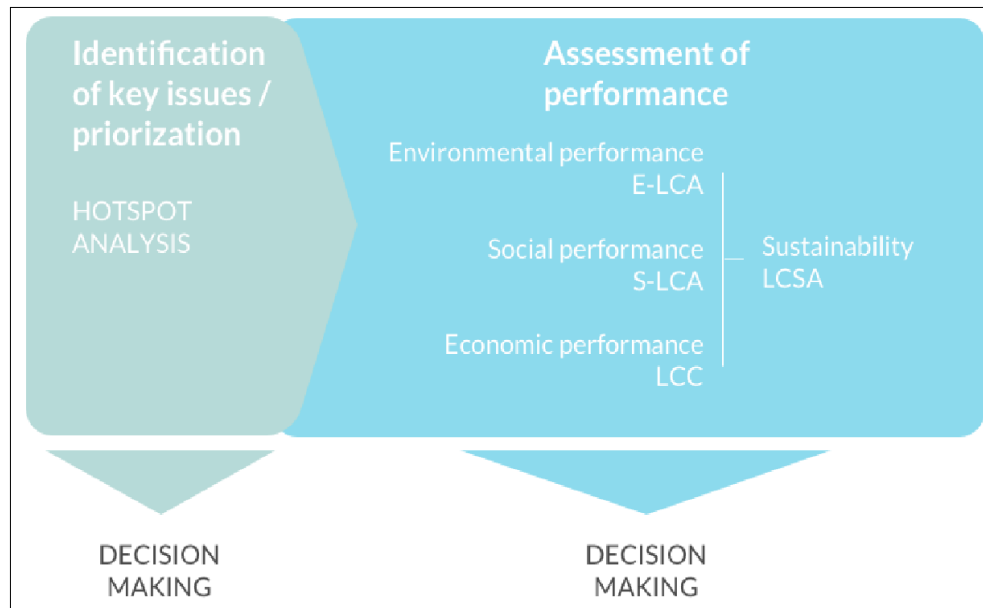
The LCT is considered the main concept, as it foresees the entire process of sustainable development covering all phases of the life cycle, in order to identify priorities for interventions based on the areas where there are greater opportunities. It is about understanding the environmental, social, and economic impacts in the decision-making management process (UNEP/SETAC, 2012).

The second concept is Life Cycle Management (LCM), which is based on the integration of LCT into management practices, that is, managing the entire life cycle of a system. A "system" can be a product, process, service, or even an organization, with the sole purpose of providing societies with more sustainable goods and services. Thus, a more effective way to support sustainable decisions is through the application of these concepts, combined with existing assessment tools (UNEP/SETAC, 2007). It is noteworthy that the LCT and LCM are considered qualitative studies.

2.1.1 Life Cycle Tools

Tools are life cycle approaches that aid decision making through the modeling and analysis of life cycle data for a product or service. The choice of the tool used is based on what one wants to achieve, with the definition of objectives and the scenario of action. It is important to highlight the magnitude of the life cycle measures that, when adopted, result in savings benefits, from the performance of the supply chain to the efficiency of internal operations. There is also a likelihood of increased production capacity and increased institutional capacity for innovation (LCT, 2021). Figure 2 is represented an overview of the main life cycle tools.

Figure 2 - Life Cycle Tools.



Source: Life Cycle Thinking (LCT, 2021)

2.1.1.1 Hotspot Analysis (HPA)

The Hotspot Analysis (HPA) is a useful and effective analytical tool in identifying areas to be prioritized for action. It allows for rapid assimilation and analysis of diverse information, including studies based on life cycle, market, scientific research, expert opinion, and specific stakeholder concerns. The HPA evaluate the environmental performance that combines environmental and socioeconomic data with commercial information, allowing to trace environmental pressures and impacts along the production chain (LC Initiative, 2019)

2.1.1.2 Life Cycle Environmental Assessment (E-LCA)

The Life Cycle Environmental Assessment (E-LCA) is an analysis tool or technique that assesses environmental performance through the life cycle of the product or service. The extraction and consumption of resources (including energy) as well as supplied to air, water and soil are quantified at all stages of the life cycle. From there, the environmental contribution potential in each impact category is evaluated. These categories include climate change, human toxicity and ecotoxicity, ionizing radiation and deterioration of primary resources (UNEP/SETAC, 2009).

2.1.1.3 Social Life Cycle Assessment (S-LCA)

The Social Life Cycle Assessment (S-LCA) is a tool applied to assess the social and sociological aspects of products, their actual and potential impacts (positive and negative), in relation to their life cycle. This tool includes everything from the extraction and processing of raw materials, manufacturing, distribution, use, reuse, maintenance, recycling, and final disposal of the product. An S-LCA uses generic and site-specific data that can be quantitative, semi-quantitative or qualitative and complements such as environmental analyzes and production and consumption economics (UNEP/SETAC, 2009).

2.1.1.4 Life Cycle Costing (LCC)

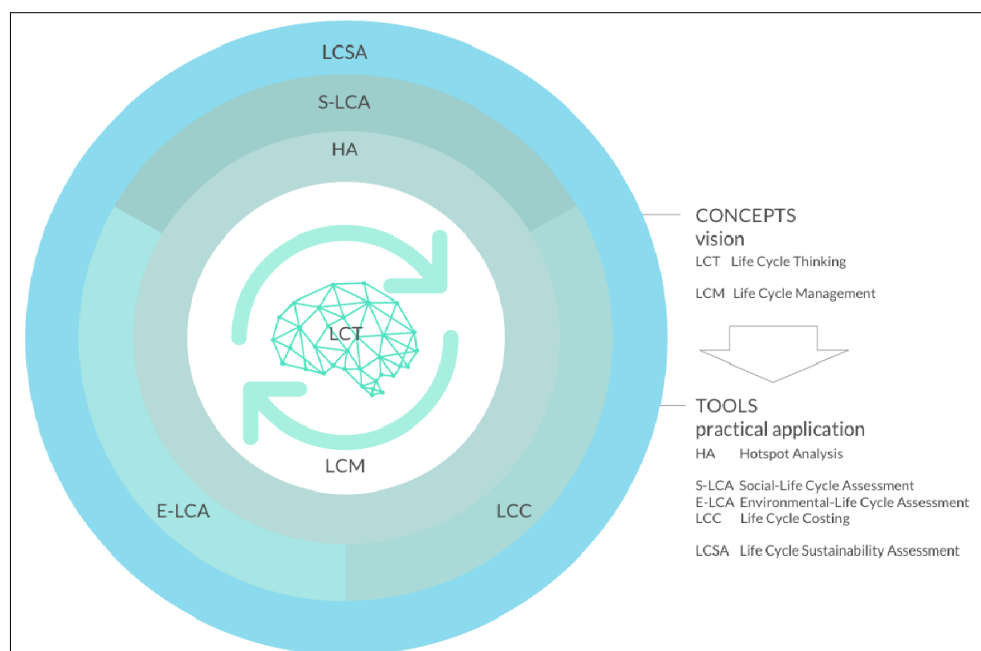
The Life Cycle Costing (LCC) is a tool that aims to assess all costs associated with the life cycle of a product or service. They are directly linked by one or more agents in the product's life cycle (supplier, manufacturer, consumer, and/or a final disposal), with the inclusion of positive or negative externalities for a society, which are available to be internalized in a decision future (Swarr, et al., 2011).

While the E-LCA has been standardized on the ISO 14040 series, the LCC and the S-LCA, are in line with the ISO 14040 (2006) framework, but differ in certain respects. There are no specific standards for LCC and S-LCA.

2.1.1.5 Life Cycle Sustainability Assessment (LCSA)

Based on the definitions and concepts about the life cycle, it becomes possible to identify how the applications of different tools work, supported by qualitative and quantitative data. This data provides us with an adequate means of evaluating the impacts arising from evaluated processes and also identifies the environmental, social and economic benefits. In this way, it is part of the combination and evaluation of acts and/or benefits, in order to integrate them into the decision-making process. This tool, Life Cycle Sustainability Assessment (LCSA), emerged as a response to the challenge of integrating and encompassing the three dimensions in the development of the LCSA (UNEP/SETAC, 2011). Figure 3 is represented an integration between concepts and tools from the previous life cycle.

Figure 3 - Life cycle concepts and tools.



Source: Life Cycle Thinking (LCT, 2021)

LCT is the key to realizing this strategy towards sustainability, allowing people, companies and colleagues to understand their role and identify what actions should be considered at the right time, and discovering creative ways to face the challenges. With the common goal of bringing LCT to decision makers, Life Cycle Initiative published in 2020 the Progress Report, in order to generate consensus on LCA methodologies and provide technical and policy support to achieve the goal of sustainable development (LCT, 2021).

2.2 What is LCA?

With the growing awareness of the importance of environmental protection and the possible actions associated with products, both manufactured and consumed, it has become necessary to develop methods to better understand and address the impacts. One of the techniques under development for this purpose is the LCA, according to International Organization for Standardization - ISO 14040 (2006) and 14044 (2006).

ISO14040 (2006) presents LCA as a technique to assess environmental and potential aspects associated with a product or service. This technique can also be considered a valuable tool for dealing with information about real impacts throughout the life cycle of products, from raw material acquisition, through production, use, post-use treatment, recycling and final disposal. Product life cycles involve material, energy and economic flows. Which, in turn, involves local acts, consumers and all authors in the chain (UNEP/SETAC, 2009).

Quantifying the potential impacts of LCA has its roots in the natural sciences. Flows are based on baseline data and baseline models (or resource consumption) are based on empirical data. In addition to the scientific core, an LCA requires the value judgment needed to assess the overall impact of a product system. The LCA employs value judgment consistently and transparently and, in some cases, allows practitioners to make modeling choices based on their own values, for example, in relation to the number of years in the future that impacts environmental factors should be considered in the assessment (Hauschild, et al., 2018).

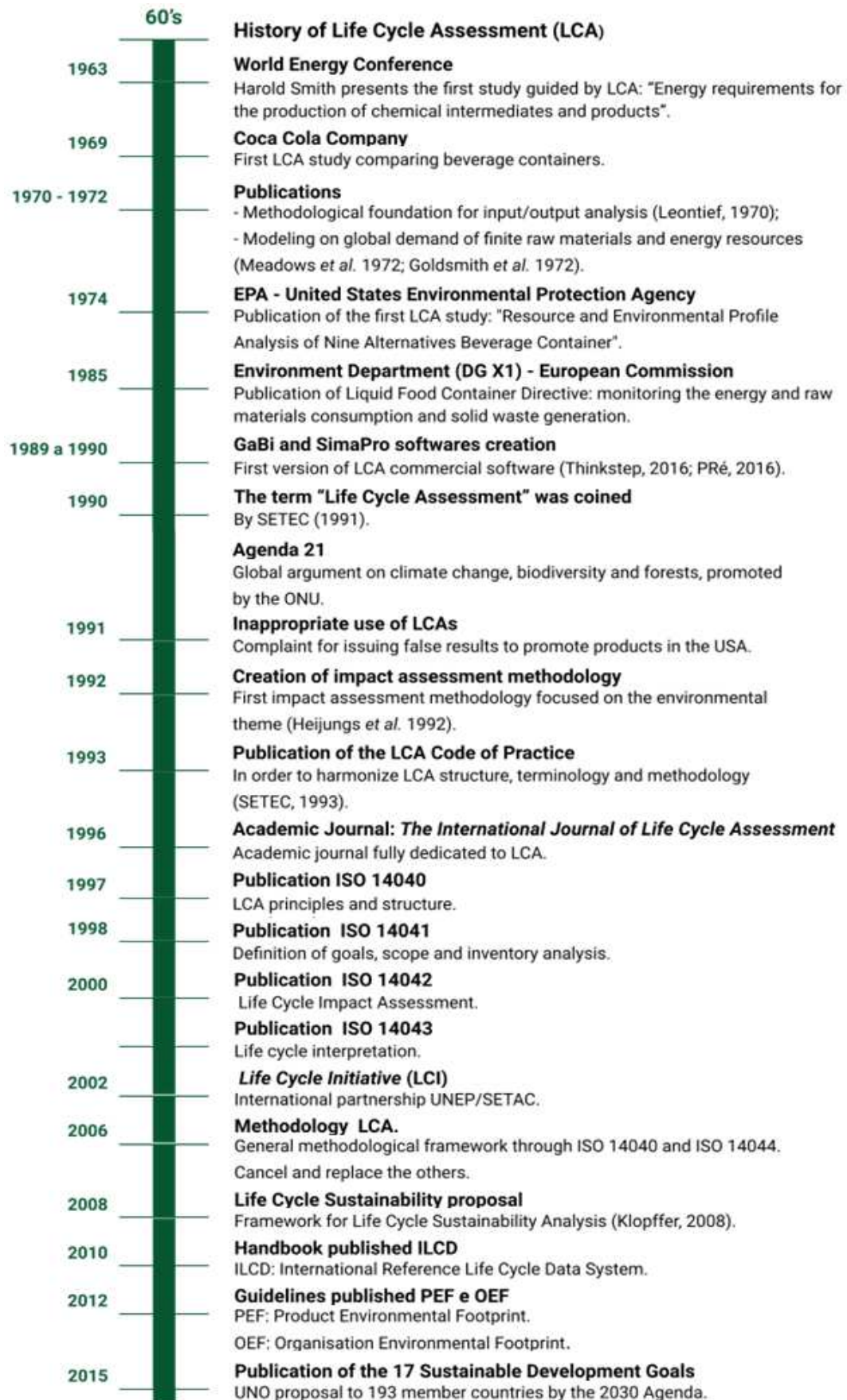
The LCA result of a product/service promotes opportunities for improvement and environmental performance of products at various points in their life cycle. It assists decision makers in strategic planning and selects relevant environmental performance indicators, including determination techniques. It also contributes to marketing with the implementation of an eco-labelling system or environmental declaration (ISO 14044, 2006; ISO 14040, 2006). These results will allow companies to know which aspects of their production are efficient, and where they can improve efficiency to reduce environmental impacts (UNEP/SETAC, 2009).

LCA can be considered one of several environmental management techniques such as Environmental Risk Assessment, Environmental Performance Assessment, Environmental Audit, Environmental Impact Assessment, among others. However, the LCA does not address the economic or social aspects of a product (ISO, 2006).

2.2.1 History and LCA evolution

Sustainable development aims to promote human well-being, contributing to current and future needs. No field of evaluation of products and processes, methodologies, techniques, and tools are developed to promote an improvement in the environmental and social conditions throughout the life cycle of a product. Since the 1960s, several efforts have been made to promote the pillars of sustainable development in a coherent and integrated manner in a productive process (Hauschild, et al., 2018; EPA, 2006; Guinée, et al., 2001). Figure 4 is illustrated the entire historical context of LCA.

Figure 4 - History of LCA.



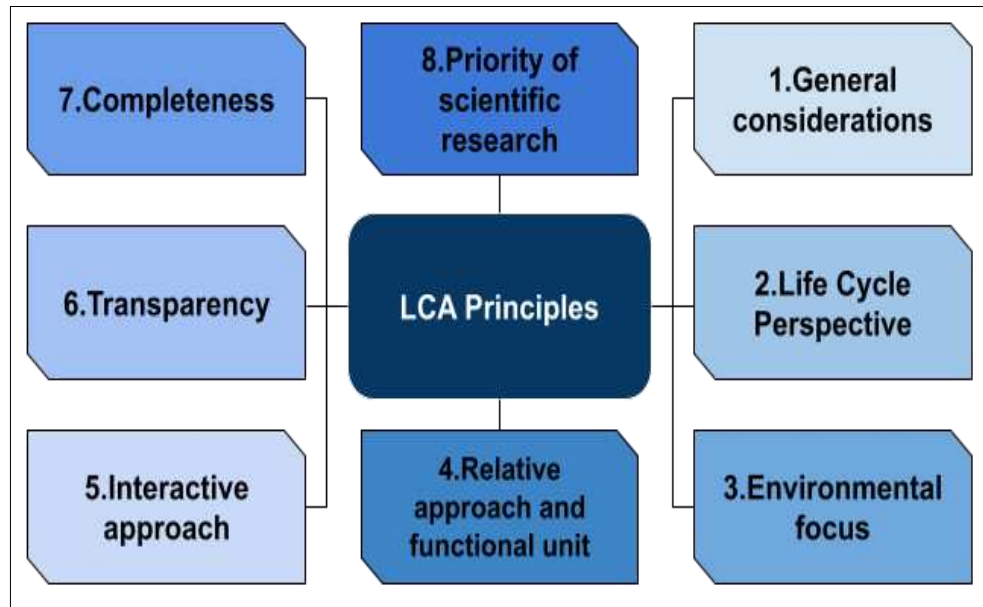
Source: Hauschild, et al., (2018), EPA, (2006), GUINÉE, et al., (2001), adapted by the author.

2.2.2 Methodological framework for LCA - ISO 14040

2.2.2.1 LCA Principles

The LCA principles are fundamental and are recommended to be used as a guide for decisions related to both planning and conducting an LCA. Figure 5 are considered the eight principles established by ISO 14040 (2006).

Figure 5 - Principles of LCA.



Source: ISO 14040 (2006), adapted by the author.

From an LCA perspective, the entire life cycle of a product is considered, from the extraction and acquisition of raw materials, manufacturing, use, post-use treatment, recycling and final disposal. LCA focuses on the environmental aspects and impacts of a production system. LCA is a relative approach structured around a functional unit. This functional unit defines what is being studied based on the Life Cycle Inventory (LCI). The iterative approach contributes to the completeness and consistency of the study and reported results. Demanding the complexity of the LCA, the solution is an important guiding principle in the execution, in order to guarantee an interpretation of the results (ILCD, 2014).

2.2.2.2 LCA Phases

According to ISOs 14040 and 14044 (2006), LCA has four phases of the study, starting with the definition of the objective and scope, moving on to an inventory analysis phase and impact assessment study, and finally the phase of interpretation of data.

The scope of an LCA depends directly on the intended object or use of the study. The depth and breadth of the LCA can vary considerably depending on the purpose of the particular study. A LCI analysis phase is the verification of the data from an inventory against the input/output of a system. This phase involves the collection of base data to achieve the objectives of the study in question. The Life Cycle Impact Assessment (LCIA) phase is the third phase of the LCA. The purpose of the LCIA is to provide additional information to assist in evaluating the results of a product system's LCI category to better understand its environmental significance. Life cycle interpretation is a final phase of the LCA procedure, in which the results of an LCI and/or an LCIA are summarized and discussed as a basis for carrying out

recommendations and decision making in accordance with the objective definition and scope (ILCD, 2014; ISO 14044, 2006).

2.2.2.3 Environmental tools

Environmental impacts are usually defined through a LCA. Actual research on sustainability and Sustainable Development (SD) remains an open question. The indicators used to measure SD need to be developed to provide a basis for decision-making. Several different concepts and methods have already been developed for such as assessments, protection and/or social processes, products or activities (Cucek, et al., 2012).

Environmental tools such as Ecological Footprint (EF), Carbon Footprint (CF), Energy and Emergy Analysis, Material flow analysis, among others, were developed to conceptualize, quantify and guide on direct effects and indirect effects of human activity in the environment. These tools have a number of common characteristics and can be mathematically reduced to similar analyzes (Patterson, et al., 2017). Thus, the evaluation of environmental studies becomes more judicious when there is a combination of environmental accounting tools, not limited to just one perspective or criterion.

A "footprint" is a quantitative measure that states how human activities may or may not impact global sustainability (UNEP/SETAC, 2015). Hoekstra and Chapagain (2007), present tools such as footprints, used for an assessment of sustainability and its components, such as Rees (1992) creator of the Ecological Footprint (EF) and Hoekstra (2003) developer of the Water Footprint (WF). It is understood that the Carbon Footprint (CF) was developed through the derivation of the Global Warming Potential, in the early 2000s, defined by Hogevoold (2003). The authors Galli, et al., (2012) defined Carbon Footprint (CF), Ecological Footprint (EF) and Water Footprints (WF) as the "footprint family".

Studies proposed by Cucek, et al., (2012) compared the connection between different Footprint analysis tools. According to Postnote (2006) in the UK, considers CF the amount of CO₂ and other greenhouse gases (GHGs) emitted throughout the life cycle of a process or product; Dadd (2007) presents the CF as a result of LCT, applied to global warming; Wiedmann and Minx, (2007), define CF as an exclusive measure of direct and indirect inherited CO₂ throughout a life cycle. Among the tools for assessing the footprint, the CF calculators are the main tools used.

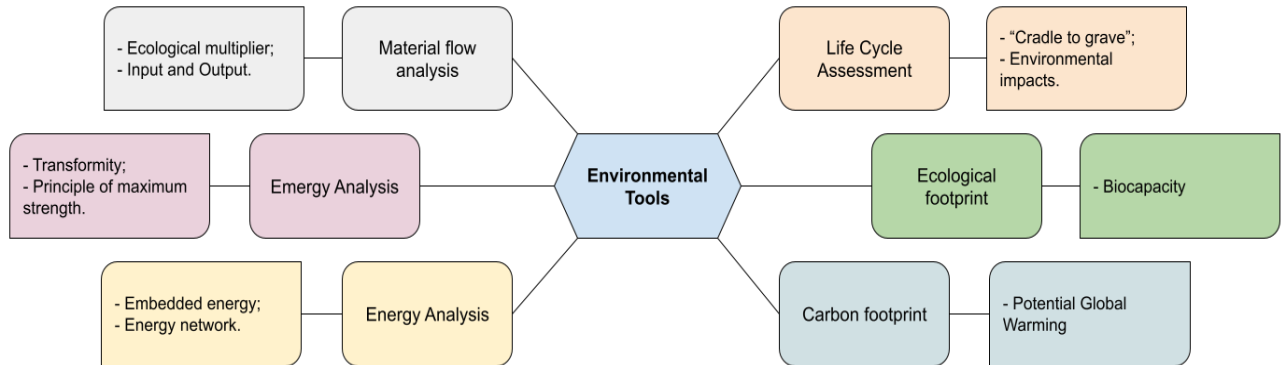
Environmental problems are related in one way or another to energy and thermodynamics, as energy is involved in all life cycles of a process. This tool was developed in the early 1970s, with a decline in interest in the 1980s with the advance of the water crisis (Patterson, et al., 2017). LCA can be applied to analyze energy systems or perform a separate analysis of energy aspects of a life cycle (Haes & Heijungs, 2007). Another important tool is the Exergetic Analysis, suitable for general statistical use, as a measure of stocks and resource flows, in addition to measuring the transfer of environmental waste (Ayres, et al., 1998).

Emergy Analysis quantifies the environmental work required to generate (ecosystem) goods and services used by humans. On the other hand, an LCA analyzes the performance of human processes and dominated systems. It is claimed that the use of inventory modeling principles behind the LCA method can improve an Emergy Analysis synthesis, which can be seen as a complementary tool, rather than an alternative, to impact assessment metrics cycles existing lives (Raugei, et al., 2014).

A material flow analysis has traditionally been used to track the production, use and consumption of materials (Hawkins et al., 2007). In this way, the application of a combined approach of Material Flow Analysis and LCA is commonly used to evaluate a complex production system. However, they are required to establish the form independently,

rather than jointly (Turner et al., 2016). Figure 6 is presented the comparison of environmental accounting methods and their main concepts.

Figure 6 - Comparison of Environmental Accounting Methods.



Source: Patterson, et al., (2017), adapted by the author.

2.2.3 LCA accounting structure: input, output and impact assessment data

2.2.3.1 The Life Cycle Inventory (LCI)

As described in the ISO 14040 (2006), LCA is a compilation and assessment of the environmental inputs, possibilities and impacts of a system product throughout its life cycle (ISO, 2006). The LCI is considered a crucial phase of LCA, being this a second phase, as it deals with the quantification and accumulation of data of inputs and processes of a system. Thus, the LCI method chosen must comprise the calculation technique, the relative advantages and limitations for the intended purpose (Islam, et al., 2017).

By quantifying requirements such as energy and raw material consumption, atmospheric effects, water consumption, solid waste generation, among other information, LCI directly interferes in the LCA of a product, process or activity (EPA, 2006). According to EPA documents (1993 and 1995) define the four steps of a LCI: process flow diagram, data collection plan, data collection, and outcome evaluation.

Suh and Huppes (2005), describe the existence of six methods of compilation of the LCI, namely: Process Flow Diagram, Product System Matrix Expression, LCI based on Input/Output, Layered Hybrid Analysis, Hybrid Analysis based on Input/Output and Integrated Hybrid Analysis. The authors concluded that for LCA studies, an input/output LCI database is more available and develops in regionalized cases, linked to a local system.

According to Islam, et al., (2017), the LCI has evolved, becoming a more robust tool for sustainable practices. Different LCI methods imply different levels of complexity and data requirements. As there are a large number of LCA software available on the market, scientific validation of LCI methodologies is possible. The authors concluded that in a faster ecological manufacturing decision, the LCI Input/Output is adequate, however, some data related to the process available in Hybrid Input/Output database, these provide a better result.

Guinée, et al., (2001) considers the ISO (2006) standard LCA, a biophysical accounting framework used to catalog the input materials of energy and natural resources that will provide in linked with each stage of the life cycle of a product. LCI theory in terms of its quantitative contributions, a specific set of environmental impact categories.

The LCA database most used today in scientific studies is Ecoinvent, with about 4,500 users in more than 40 countries, containing international LCI data on energy supply, resource extraction, material origination, products chemicals, metals, agriculture, waste management and transportation services. Each dataset is provided as a unit process

and aggregate system process. In addition, reports are published with information on modeling procedures and assumptions, with databases specifically adapted to openLCA (GreenDelta, 2022).

Burhan, et al., (2020), describes Ecoinvent as an institution responsible for managing the main international database for LCA, based in Switzerland, published in September 2019 in its database, unprecedented results for Brazilian products. The updating of Brazilian data was made possible by the ICVAgroBR project, coordinated by Embrapa Meio Ambiente and financed by the Sustainable Recycling Industries (SRI) program of the Economic Affairs Secretariat of the Swiss government (Folegatti Matsuura, et al., 2017). A total of 632 new datasets were integrated into the new version of Ecoinvent, including LCI of some of the main Brazilian agricultural products, which contributes to the increase in their occurrence in the international market, which is increasingly demanding in terms of aspects environmental (Embrapa, 2019).

The Brazilian Institute of Information in Science and Technology (IBICT) in partnership with the Brazilian Agricultural Research Corporation (Embrapa) Environment, promotes the structuring of the National Bank of LCI of Brazilian Products (IBICT, 2020, 2021). According to Rodrigues, (2020), this database should reach 300 inventories available, mostly products from the agricultural chain. It also states that when the event is produced from its initial phase, it becomes a slower and more costly process. If the inventory is available in a database, the authors will be able to carry out the analysis, generate studies, without the need for complete data surveys.

During the structuring of the agreement that culminated with the availability of Brazilian data in the ecoinvent database, Embrapa formalized the donation of data to the National Bank of LCI, the SICV Brasil (SICV, 2020), managed by the Brazilian IBICT. In addition to international recognition, an update of the data will contribute to the practice of increasing access to national data by Brazilian professionals and researchers (Embrapa, 2019).

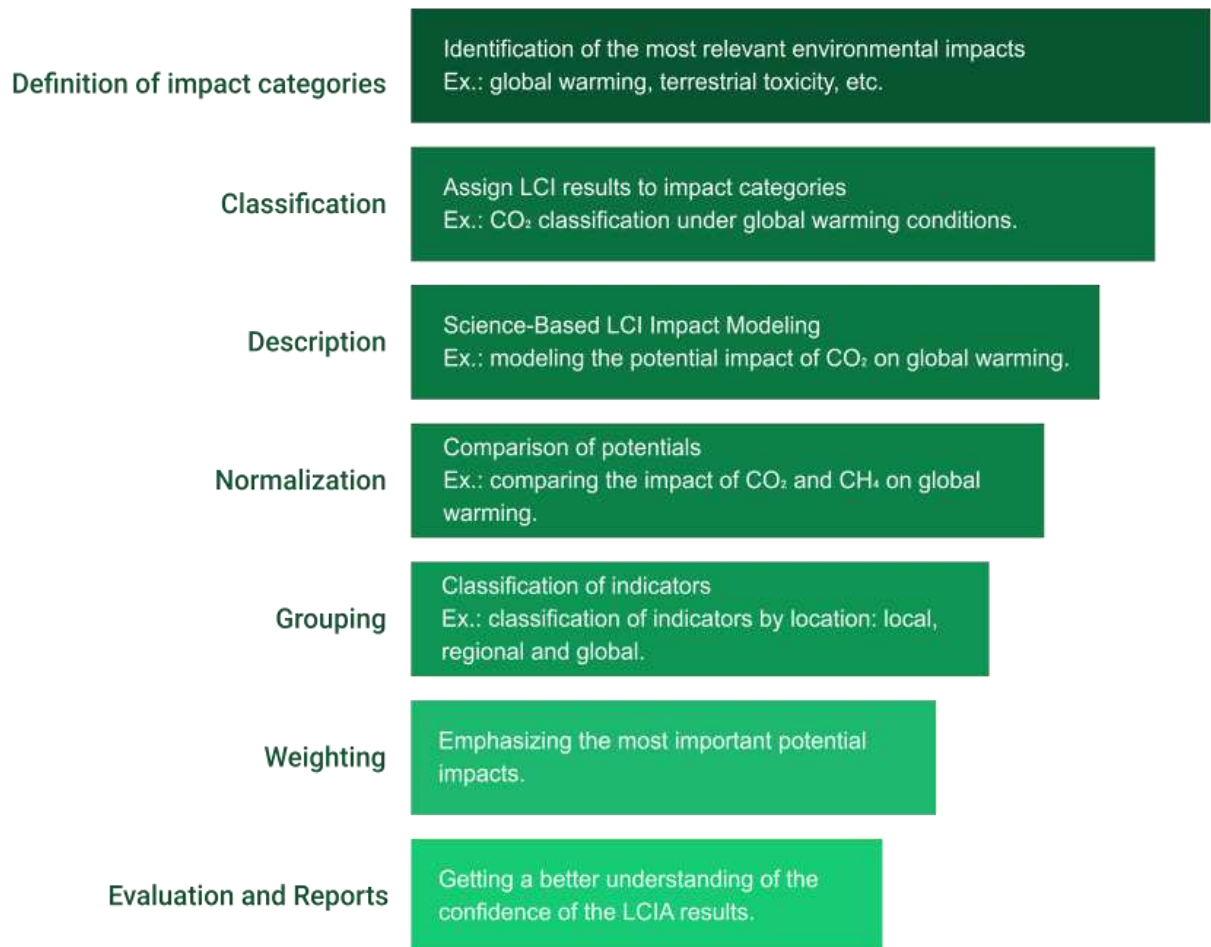
The inventory process can be considered a complete and more complex research, which can generate environmental product declarations, which is another way of demonstrating its environmental performance (Rodrigues, 2020). When documenting the results of the LCI, it is important to describe the entire methodology covered, define the applicable systems and the thresholds that have been adjusted, and any assumptions made in performing the inventory analysis. The result of the inventory analysis is a list containing the amounts of pollutants released into the environment and the amount of energy and materials consumed. This information can be organized for the life cycle stage (EPA, 2006).

The diversity of sources for LCI and LCIA databases contributes considerably to environmental studies. However, there is great variability in the nomenclature used in each font. In this way, the openLCA software contributes to the organization of different database flows and LCIA methods (GreenDelta, 2023).

2.2.3.2 LCIA - Life Cycle Impact Assessment

The Life Cycle Impact Assessment (LCIA) phase is considered an assessment of the potential related to human health and the environmental impacts identified during the LCI, contemplating the third phase of an LCA. The LCIA aims to provide an aggregation of inventory data using additional information, such as (internationally accepted) performance levels, to understand / translate the magnitude and importance of the results for impact assessment (UNEP/SETAC, 2009). The steps to be followed as shown in the Figure 7, comprise an assessment of the impact of the life cycle, according to EPA (2006).

Figure 7 - Stages of Life Cycle Impact Assessment – LCIA



Source: EPA (2006), adapted by the author.

The ISO 14042, LCIA (ISO 2000), replaced by ISOs 14040 and 14044 (2006), describe LCIA in three stages, namely: impact category selection, correlation of LCI results and calculation of results of category indicators, which in turn will guarantee the results of category indicators. They point out as optional elements the calculation of magnitude, grouping and weighting.

LCIA analyzes according to (UNEP/SETAC, 2009) result in criteria for three areas of protection from damage: human health, ecosystem quality and natural resources. The definition of these areas aims to safeguard the values considered important to society. When considering the protected area “human health” it can be used aggregate impacts of morbidity and mortality as an indicators to measure damage to human health. Several methodological developments over the final decade indicate the need for an update to the LCIA Framework and guidance on cross-cutting issues within the LC Initiative.

First, it is observed the lists of impact categories verified as midpoint, damage level and data level according to a protection area. It is noteworthy that there are more flow items to be considered. Impact characterization models can link your LCI to the midpoint impact level or to the damage level, or directly to the damage level according to protected area, aggregated into broad categories. The weighting of damage category scores can include normalization, this is an optional step. Normalization and weighting can also be performed at the level of the midpoint impact indicator (Verones, et al., 2017).

Finally, a final phase of the LCA process is taken, the interpretation of the life cycle. Life Cycle Data Interpretation (LCDI) is seen as a systematic technique to identify, quantify, verify, and evaluate information based on all previous results, such as LCI and LCIA results (EPA, 2006).

The ISO 14044 (2006) defined the following two life cycle interpretation objectives: Analyze the results, arrive at the consequences, explain the limitations and provide recommendations based on the process of the previous LCA phases, and finally, report the results of the life cycle interpretation transparently; Provide a readily understandable, complete, and consistent presentation of the LCA results, consistent with the purpose and scope of the study.

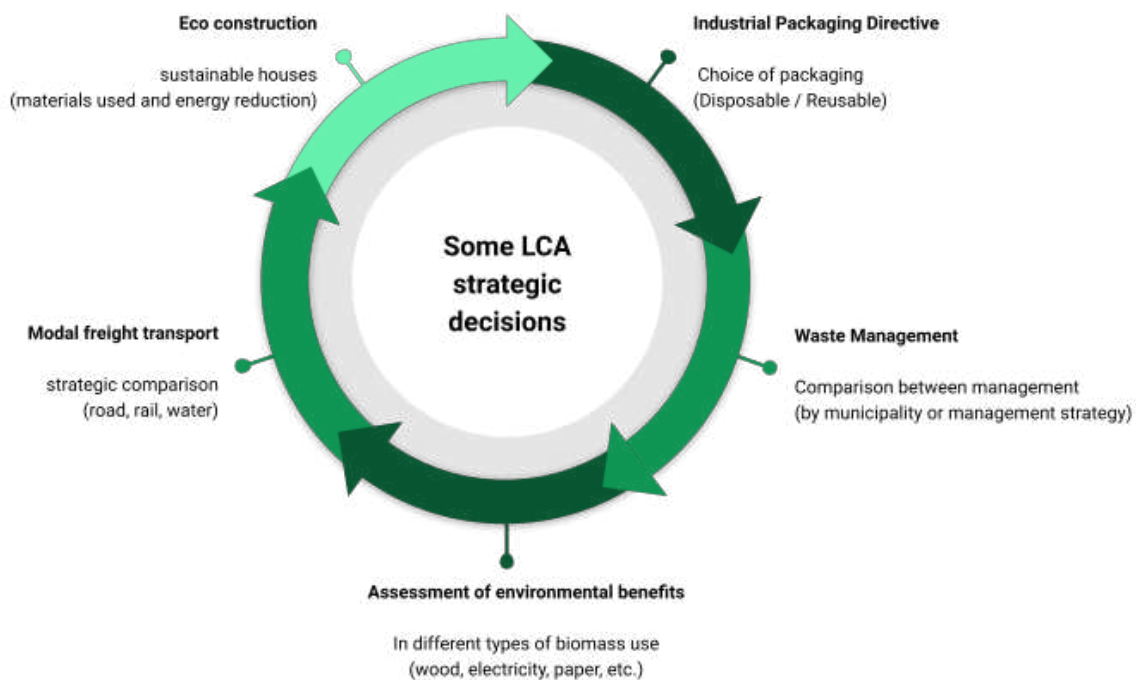
In the LCIA, several impact categories are considered, defined according to the objective and scope defined in the study. According to Pizzol, et al., (2011) the great challenge of the LCIA methodology is to evaluate the potential impact using an applicable procedure, considering a common unit of measurement, resulting in comparable data between impact categories. Another specific point is the development of methods that consider global and/or regional impacts, as has already been done in countries such as: Canada, Europe, Japan, the United States, among others. Therefore, these methods do not necessarily reflect the situation of countries like Brazil, which does not yet have specific LCIA methods for the environmental characteristics of the country itself. Methodologies are being improved and can be applied to life cycle impact assessment. (Motta, 2016), considers in his study that the carbon footprint impact category (CO₂ eq.) is the most pioneering in LCA studies to be used in Brazilian companies.

2.3 Applications and limitations of LCA

Carrying out an LCA in a production process will provide greater understanding of the system, in order to identify the necessary actions and the complexity of the product system. The technique can be used by companies, associations, academia, NGOs, governments, etc. However, evaluators need knowledge on how to use the technique and how to interpret the results (UNEP/SETAC, 2009).

The main applications of LCA are linked to analyzing the origins of problems related to a given product; the comparison of variants in the improvement process of a given product; the projection of new products; and choosing from a range of comparable products. Similar applications can be distinguished at a strategic level, dealing with public policies and business strategies (Tukker, 2000). Ecolabeling programs are becoming increasingly important for promoting sustainability as they meet all specific requirements based on life cycle information (Guinée, et al., 2001). In the Figure 8 are shown some examples of wider LCA applications.

Figure 8 - Life Cycle Assessment Strategies



Source: GUINEE et al., (2001). Adapted by the author.

The main characteristic of the LCA is its "holistic" nature, which is both its main strength and, at the same time, its limitation. The broad scope of a product's LCA can only be achieved at the expense of simplifying other aspects. In the Figure 9 are listed the main limitations of LCA, by Ginée, et al., (2001), EPA (2006), UNEP/SETAC, (2009).

Figure 9 - Limitations of LCA.

01	Localized impacts	<ul style="list-style-type: none">• Identifies impacts on a facility in a specific location;• Broader concept.
02	Focused on industrial physical characteristics	<ul style="list-style-type: none">• Industrial activities;• Favorable activities.
03	Market mechanisms	<ul style="list-style-type: none">• Does not include supply and demand mechanisms;• or side effects.
04	Use of technical assumptions	<ul style="list-style-type: none">• Although grounded in science, it involves a number of technical assumptions;• Choice of value.
05	Focuses on environmental aspects of products	<ul style="list-style-type: none">• It does not address characteristics, social and others.
06	Database access	<ul style="list-style-type: none">• Limitations caused by difficult access to data;• Database in development.
07	Obsolete data	<ul style="list-style-type: none">• Unrivaled data or of unknown quality.
08	Human intervention	<ul style="list-style-type: none">• Process manual;• With decision makers.
09	Software availability	<ul style="list-style-type: none">• Limitations induced by the novelty of the technique;• Software in development.
10	Final review process	<ul style="list-style-type: none">• Questions only in the final phase;• Questions in the overall results.

Source: GINÉE (2001), EPA (2006), UNEP / SETAC, (2009); adapted by the author.

For these reasons, it is recommended that a peer review process be established and implemented at the start of any study about a product or process and in all its life cycle stages UNEP/SETAC, (2009).

3. Final Considerations

Successful utilization and capitalization of the entire LCT and LCA methodology will ultimately require your evaluators to pay attention to multiple economic, social and environmental considerations, based on rigorous approaches

to LCT and assessment and multi-objective optimization. These efforts will be essential to comply with the sector's social and environmental licenses in the regulatory, value chain and market contexts, which in turn are increasingly oriented towards compliance with sustainability in production.

Evidently, sustainability management presents major challenges and opportunities for industry. However, interventions in new technologies can be extremely promising in order to guarantee true sustainability in production. This will require an assessment and multiple considerations of economic and environmental sustainability, based on rigorous LCT and assessment approaches. It is noteworthy that the LCA of a product or process can be a comparative parameter for future assessments, as well as for data analysis in different production systems, having a comparative effect based on local information/data, bringing greater legitimacy to the results obtained.

Acknowledgments

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Review

Life Cycle Assessment Project for the Brazilian Egg Industry

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Featured Application: The topic addressed is highly relevant to the Brazilian Egg Production Industry.

Simple Summary: Promoting sustainability in food production has become fundamental to meeting the demands of the market, mainly because it presents a trend of expansion around the world. Life cycle assessment is a recognized methodology for providing quantitative information on environmental impacts caused throughout the production cycle in different categories. With the aim of providing transparent information to Brazilian producers and consumers about the impacts generated in egg production, this review presents the LCA methodology addressed in international studies based on the ISO 14040 and 14044:2006 standards. The results generally point to feed production and supply as the main point of impact on production, covering all impact categories, including Acidification, Eutrophication, Fossil Fuel Depletion, Global Warming Potential, Ozone Layer Depletion and Ecotoxicity. After quantifying emissions, it becomes possible to estimate the value of emissions per unit of eggs produced. The results obtained during the analysis will be able to promote good environmental practices and new ecological strategies, including animal welfare, food safety, the rational use of natural resources, the reduction in gas emissions and the generation of data on future scenarios.

Abstract: Brazil is among the ten largest egg producers in the world. The domestic consumption of Brazilian eggs is 99.6%, the rest being exported to more than 82 countries, with an expectation of growth in the foreign market. The Brazilian egg industry has evolved considerably in recent decades, incorporating new technologies and smart practices. However, there is no assessment of how production could become more sustainable over the years. The LCA (Life Cycle Assessment) approach aims to recognize the polluting potential, identify the environmental impacts generated and reduce these impacts throughout production. On a global scale, researchers approach LCA as a constructive and quantitative technique, and there is great interest in implementing an LCA for the Brazilian egg production sector. With the aim of introducing the LCA methodology to the Brazilian egg industry, this review presents the concept and accounting structure of LCA through LCI (Life Cycle Inventory) and LCIA (Life Cycle Impact Assessment), based on the ISO 14040 and 14044:2006 standards, to quantify the

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environmental performance of production and identify areas for future improvement, thus promoting the environmental footprint of the Brazilian egg industry.

Keywords: LCA; LCI; LCIA; agricultural sector; egg production; intensive system; sustainability

1. Introduction

According to data from the FAO (Food and Agriculture Organization) [1], the world population is expected to grow to 9.7 billion by 2050. The challenges are not limited to providing more food for a growing population but also include social, economic and environmental challenges [2]. In 2021, world egg production exceeded 86.4 million tons, compared to 87.1 million tons produced in 2020. This number represents the resumption of economic growth caused by the second year of the Covid-19 pandemic, a constant observed in Brazil and in the world [3,4]. However, the historical series of world egg production has increased by more than 100% from 1990 to the present day [3].

Brazil is among the ten largest egg producers in the world, occupying the fifth position in the world ranking, in the year 2022 [5]. According to the ABPA (Brazilian Animal Protein Association) [6], 99.6% of Brazilian egg production is destined for the national market. Only 0.4% is destined for the international market (with growth expected for the coming years), exported to more than eighty countries distributed in the regions of Africa, America, Asia, Europe, Oceania, the Middle East and the European Union. They are in the ranking of the five largest importers of Brazilian eggs in the year 2022: United Arab Emirates (6916 tons), Japan (1171 tons), Qatar (486 tons), United States of America (472 tons) and Oman (408 tons).

According to IBGE (Livestock Production Statistics Report) [7], the production of chicken eggs reached 1.03 billion dozens in the fourth quarter of 2022. The result represented an increase of 3.1% compared to the same period of the previous year and an increase of 1.3% compared to the third quarter of 2022 [7]. This number corresponds to the increase in consumption in the domestic market and the continuous growth of the production of Brazilian eggs [6], which have remained on the market because they are the lowest-priced source of animal protein and, therefore, more accessible to all social classes [4]. Some of the main challenges of modern production include promoting sustainability in the production process, contributing to the reduction in greenhouse gas emissions, the loss of biodiversity and the depletion of finite natural resources. For future sustainable poultry production, it is essential that these challenges are overcome [8].

The impact of different egg production systems is still considered a significant issue, including housing types, health, welfare and animal behavior. The intensive cage-based production system has become a subject of debate among advocates of animal welfare and protection, as well as among researchers and producers. However, in addition to animal welfare, there are many other aspects involving sustainability, including economics, environmental factors, human health, food safety and social values [9].

The predominant egg production system in Brazil is intensive, with conventional cages in sheds. It is estimated that the cage system corresponds to 95% of the total egg production. In this production system, two types of installation predominate: pyramidal, corresponding to 64%, also known as the Californian model; and vertical, corresponding to 36%, both systems differing only in the arrangement of the cages [10].

Brazilian commercial egg producers comply with regulations that address different specifications and information related to production, complementing the safety and compliance aspects of eggs distributed in the market [8]. The main regulatory bodies are the MAPA (Ministry of Agriculture and Livestock) [11], ANVISA (National Health Surveillance Agency) [12] and INMETRO (National Institute of Metrology, Quality and Technology) [13,14]. In compliance with the standards, guiding documents obtained by EMBRAPA (Brazilian Agricultural Research Corporation) [11] and ABPA (Brazilian Association of Animal Protein) [12] address the stages of production, from the origin of inputs to the final product for the consumer. In 2009, ABNT (Brazilian Association of Technical Standards) published the following NBR (Brazilian Technical Standard) as Portuguese versions: NBR ISO 14040:2009—Life Cycle Assessment: Principles and Structure [15]; and NBR ISO 14044:2009—Life Cycle Assessment: Requirements and Guidelines [16].

The agricultural sector undergoes constant changes related to economics, technology and social, environmental and marketing aspects, which occur simultaneously under different conditions and at high speeds [17]. Thus, solutions are needed for some important issues, such as the availability of natural resources, the control of the generation of pollutants and the extraction of sustainable raw materials. The main strategies used by producers are the intensification of the use of available resources and investing in management training, considering that the success in the productive activity is a function of the producer's capacity to adhere to the technological tools available [18].

Because it is an intensive production system with growing demand, it is important to carry out studies that indicate clearly and precisely how much production impacts the environment. Every production process generates the depletion of natural resources, material flows, energy expenditure and increased emissions along the production chain. Another important aspect is the specific assessment of the impacts of this chain. From a broader perspective, all inputs should be analyzed with the objective of predicting mitigation practices and proposed solutions. However, there is a lack of studies on production scenarios and coefficients that integrate the environmental impacts resulting from the inefficiency in the use of inputs in egg production [19].

Initially, the LCA (Life Cycle Assessment) was carried out as an environmental tool to be applied in industry in 1960 in Europe [19]. In recent years, LCA has been used in the agricultural sector in response to the growing demand for information about production and its production chain [20]. However, there are still challenges, such as encouraging producers to use LCA as a sustainable production tool as a way to guarantee the reduction in impacts and the generation of future profits. The LCA approach facilitates the identification of opportunities for improvement and resource efficiency, together with the purpose of reducing the emissions, acknowledging of the potential load transfer in different types of impacts and/or different stages of the supply chain and proposing results for decision makers. The LCA tool provides a basis for sustainable interventions, analyzing the main variables of the supply chain [20].

In view of the above, the objective of this review is to present, in general, the environmental LCA approach of an egg farm, from the cradle to the gate, according to ISO 14040 and 14044:2006 [21,22], in order to identify which tools are available so that this assessment can promote the environmental footprint of the egg industry in Brazil.

2. Life Cycle Assessment (LCA)

2.1. Conceptualization

With the growing awareness of the importance of environmental protection and the possible actions associated with products, both manufactured and consumed, it has become necessary to develop methods for better understanding and addressing such impacts. One of the techniques under development for this purpose is the LCA, according to ISO 14040 and 14044:2006 [21,22].

These standards [21,22] present LCA as a technique for assessing the potential environmental impacts associated with a product. This technique can also be considered a valuable tool for dealing with information about real impacts throughout the life cycle of products, from the acquisition of raw materials through production, classification, use, post-use treatment, recycling and final disposal. The product life cycles involves material, energy and economic flows. These, in turn, involve local impacts, consumers and all actors in the supply chain [23].

The LCA employs value judgments consistently and transparently and, in some cases, allows practitioners to make modeling choices based on their own values. As an example, one can cite the number of years into the future that environmental impacts should be considered in the assessment [24].

The LCA results of a product or process promote opportunities for improvement and environmental performance at various points in its life cycle. In this way, it is possible to assist decision makers in strategic planning and in the management of relevant environmental performance indicators [25,26]. It is also possible to contribute to marketing, through the implementation of an ecological labeling system, such as, for example, disclosing the environmental footprint of the product or process as a communication strategy [27]. However, the conclusion of an LCA allows companies to know how to quantify the sustainability of a product or process and which environmental aspects can be improved in order to allow for the reduction in potential environmental impacts [28].

LCA can be considered one of several environmental management techniques such as Environmental Risk Assessment, Environmental Performance Assessment, Environmental Audit and Environmental Impact Assessment, among others. However, the LCA does not address the economic or social aspects of a product [22]. According to ISO 14040 and 14044:2006 [21,22], LCA consists of four phases, starting with the definition of the objective and scope, moving on to an inventory analysis phase and impact assessment study and, finally, ending with the phase of interpretation of data, as illustrated in Figure 1.

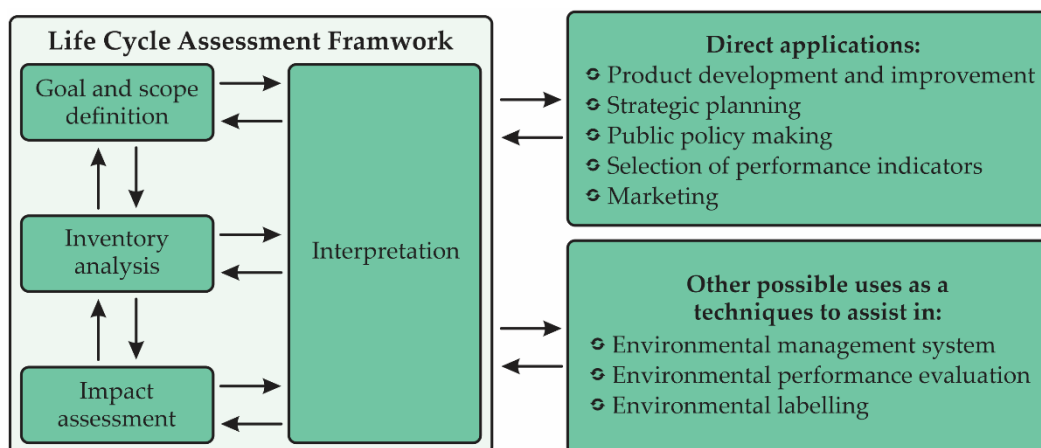


Figure 1. Life Cycle Assessment Framework, according to the ISO 14040 and 14044:2006 [21,22].

The scope of an LCA depends directly on the intended object or use of the study. The depth and breadth of an LCA can vary, depending on the purpose of the study. An LCI (Life Cycle Inventory) analysis phase is the verification of the data from an inventory against the input/output of a system. This phase involves the collection of base data to achieve the objectives of the study in question. The LCIA (Life Cycle Impact Assessment) phase is the third phase of the LCA. The purpose of the LCIA is to provide additional information to assist in evaluating the results of a product system's LCI category to better understand its environmental significance. Lifecycle interpretation is the final phase of the LCA procedure, in which the results of an LCI and/or an LCIA are summarized and discussed as a basis for carrying out recommendations and decision making in accordance with the objective definition and scope [22,25].

2.2. Accounting Structure

2.2.1. Life Cycle Inventory (LCI)

As described in the ISO 14040 and 14044:2006 [21,22], an LCA is “a compilation and assessment of the environmental inputs, possibilities and impacts of a system product throughout its life cycle”. The LCI is considered a crucial second phase of LCA, as it deals with the quantification and accumulation of input data and the processes of a system. Thus, the LCI method chosen must comprise the calculation technique, its relative advantages and its limitations for the intended purpose [26].

By quantifying requirements such as energy and raw material consumption, atmospheric emissions, water consumption and solid waste generation, among other information, LCI directly interferes in the LCA of a product, process or activity [27]. The EPA (Environmental Protection Agency) documents (1993 and 1995) [27] define the four steps of a life cycle inventory: process flow diagram, data collection plan, data collection and outcome evaluation.

According to Suh and Huppel [28], there are six methods of compilation of the LCI (Life Cycle Inventory), namely: Process Flow Diagram, Product System Matrix Expression, LCI based on Input/Output, Layered Hybrid Analysis, Hybrid Analysis based on Input/Output and Integrated Hybrid Analysis. These authors concluded that, for LCA studies, an input/output LCI database is more available and developed in regionalized cases, linked (connected) to a local system.

To Islam et al. [26], the LCI has evolved significantly, becoming a more robust tool for sustainable practices. Different LCI methods imply distinct levels of complexity and data requirements. As there are many LCA software available on the market, the scientific validation of LCI methodologies is possible. The authors concluded that, in a faster ecological manufacturing decision, the LCI Input/Output is adequate; however, if some data related to the process are available in the Hybrid Input/Output database, these provide a better result.

Guinée et al. [29] considered the ISO 14040 and 14044:2006 [21,22] a biophysical accounting framework used to catalog the input materials of energy and natural resources that will provide emissions associated with each stage of the life cycle of a product. LCI describes, in terms of its quantitative contributions, a specific set of environmental impact categories.

The LCA database most used today in scientific studies is Ecoinvent [30], with about 4500 users in more than 40 countries, containing international lifecycle inventory data on energy supply, resource extraction, material origination, chemical products, metals, agriculture, waste management services and transportation services. Each dataset is provided as a unit process and aggregate system process. In addition, reports are published with information on modeling procedures and assumptions. The latest version is Ecoinvent v.3.7.1, with databases specifically adapted to OpenLCA [31].

Updating the Brazilian database was made possible by the ICVAgroBR project, coordinated by EMBRAPA Environmental [32] and funded by the SRI (Sustainable Recycling Industries) program of the Swiss government's Secretariat for Economic Affairs. A total of 632 new datasets were integrated into the new version of Ecoinvent, including life cycle inventories of some of the main Brazilian agricultural products, contributing to the increase in their occurrence in the international market, which is increasingly demanding in terms of environmental aspects [33].

The IBICT (Brazilian Institute of Information in Science and Technology) [34], in partnership with the EMBRAPA Environment [32], promotes the structuring of the National Bank of Life Cycle Inventories of Brazilian Products [35]. According to Rodrigues [36], this database should reach 300 available inventories, mostly products from the agricultural chain. This author also claims that the inventory is produced from its initial phase; it becomes a slower and more costly process. If the inventory is available in a database, the authors will be able to carry out the analysis and generate studies without the need for complete data surveys. During the structuring of the agreement that culminated with the availability of Brazilian data in the Ecoinvent database [37], EMBRAPA [33] formalized the donation of data to the SICV Brazil (National Bank of Life Cycle Inventories) [38], managed by the IBICT [39]. In addition to international recognition, an update of the data will contribute to the practice of increasing access to national data among Brazilian professionals and researchers [33].

The inventory process can be considered a complete and more complex survey, which can generate environmental declarations of the product, which is another way of demonstrating its environmental performance [36]. When documenting the lifecycle inventory results, it is important to describe the entire methodology covered and define the applicable systems and thresholds that were adjusted and any assumptions made in carrying out the inventory analysis. The result of the inventory analysis is a list containing the amount of pollutants released into the environment and the amount of energy and materials consumed in the production process [27].

2.2.2. Life Cycle Impact Assessment (LCIA)

The LCIA (Life Cycle Impact Assessment) phase is considered an assessment of the potential impacts related to human health and the environment identified during the LCI, contemplating the third phase of an LCA. The LCIA aims to provide an aggregation of inventory data using additional information, such as (internationally accepted) performance levels, to understand/translate the magnitude and importance of the results for impact assessment [23]. Life Cycle Data Interpretation is seen as a systematic technique for identifying, quantifying, verifying and evaluating information based on all previous results, such as those from LCI and LCIA [27]. ISO 14040 and 14044:2006 [21,22] defined the following two lifecycle interpretation objectives: 1) analyze the results, arrive at the consequences, explain the limitations, provide recommendations based on the process of the previous LCA phases and, finally, report the results of the life cycle interpretation transparently; and 2) provide a readily understandable, complete and consistent presentation of the LCA results, consistent with the purpose and scope of the study.

For an LCIA, several impact categories are selected according to the objective and scope defined in the study. According to Mendes et al. [40], traditional impact categories are defined by resource depletion, land use, climate change, stratospheric ozone depletion, human toxicity, aquatic ecotoxicity, terrestrial ecotoxicity, the formation of photo-oxidants, acidification and eutrophication. Depending on the requirements of the study, additional impact categories may be

considered. Figure 2 presents the stages of the Life Cycle Impact Assessment (LCIA) according to the definitions of the impact categories.

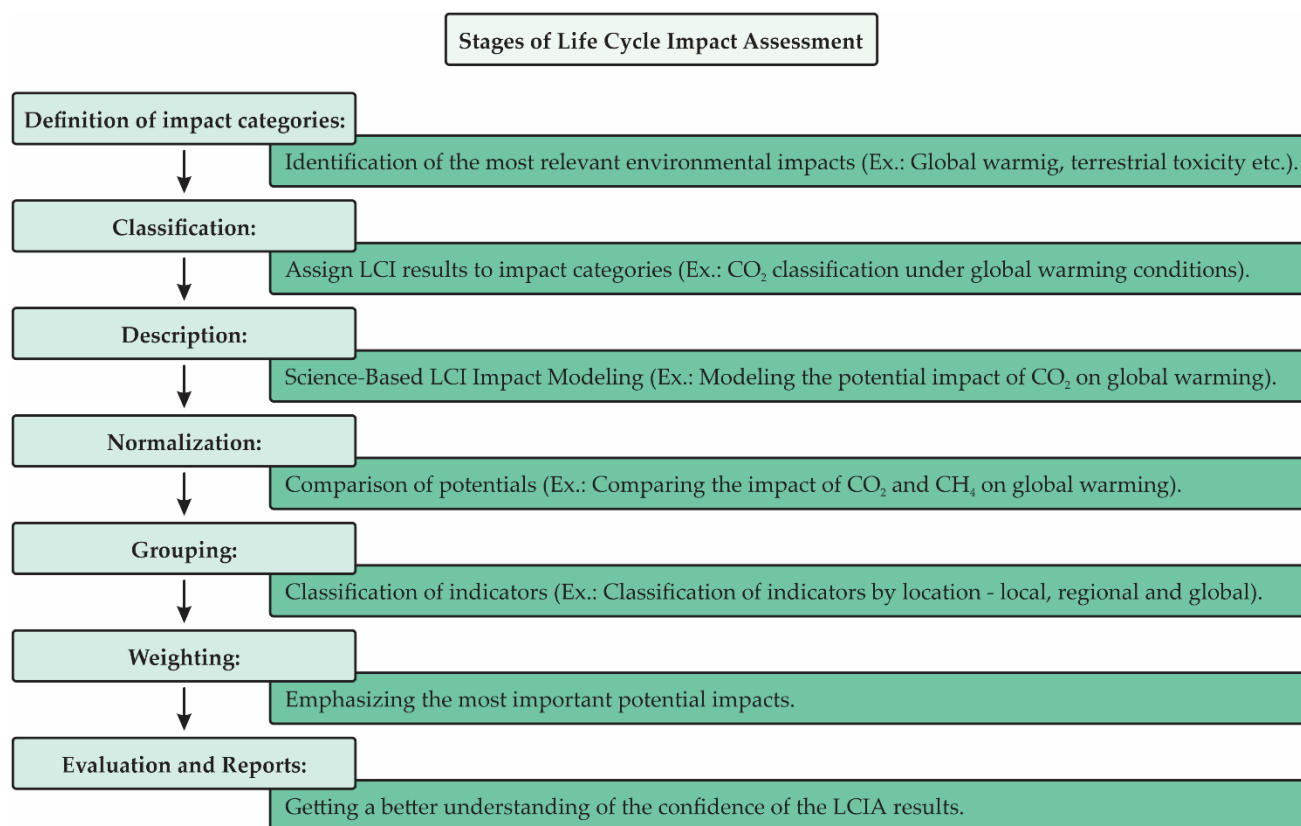


Figure 2. Stages of Life Cycle Impact Assessment (LCIA). Source: EPA [27]—Adapted by the author.

According to Pizzol et al. [41], the great challenge of the LCIA methodology is to assess the potential impact using an applicable procedure, considering a common measurement unit and providing comparable data between impact categories. Another important point is the development of methods that consider global impacts and/or impacts relative to specific regions, such as specific countries: Canada, Europe, Japan and the United States. Thus, these methods do not necessarily reflect the situation of countries such as Brazil, which still does not have specific LCIA methods for the country's environmental characteristics [27].

3. Life Cycle Assessment in Egg Production

In this review, the life cycle assessment tool addressed will be the environmental life cycle assessment. This is considered a widely used tool for assessing the intensity of resources used and product emissions from a supply chain perspective [42].

The ISO standardized framework [21,22] for LCA provides prescriptive guidance for characterizing inputs and emissions of materials and energy along product supply chains and for quantifying how these flows contribute to a variety of resources used, human health and potential environmental impacts.

On a global scale, researchers' approach LCA as a constructive and quantitative technique, showing great interest in implementing LCA for the egg production process. Table 1 describes the current LCA studies, between the years 2018 and 2022, in the egg production process, its structure and considerations.

Table 1. Literature review on Live Cycle Assessment in the egg production process, published between 2018 and 2022.

Reference, Local	Article	Conclusions
Guillaume et al. (2022) [43], Czech Republic	Environmental Impacts of Egg Production from a Life Cycle Perspective	Feed composition and manure management are the factors with the greatest environmental impact, and the results suggest FCR ¹ .
Turner et al. (2022) [44], Canada	Life cycle assessment of contemporary Canadian egg production systems during the transition from conventional cage to alternative housing systems: Update and analysis of trends and conditions	Feed inputs are the largest contributors to the impact categories (18%–84%), followed by pullet production and manure management (10%–37% and 0.01%–62%, respectively). Conventional cages had lower impacts than all non-organic systems.
Salami et al. (2022) [45], United Kingdom	Performance and environmental impact of egg production in response to dietary supplementation of mannan oligosaccharide in laying hens: A meta-analysis	² MOS supplementation at 1.0 kg/ton improved the productive performance of laying hens and reduced the carbon footprint. Low and high ³ SBM diets reduced emissions by: dozen eggs (−0.02 and −0.03 kg CO ₂ eq); egg unit (−2.2 and −2.5 g CO ₂ eq); and kg of eggs (−0.04 and −0.04 kg CO ₂ eq).
Turner et al. (2022) [46], Canada	Environmental impact mitigation potential of increased resource use efficiency in industrial egg production systems	Potential reductions in pullet and feed consumption are up to 13.22%. The impacts are reduced by up to 17.27%.
Mitrovic et al. (2022) [47], Serbia	Assessment of Environmental Impacts from Different Perspectives—Case Study of Egg Value Chain System in Serbia	The productive chain of table eggs emitted 3.33 kg CO ₂ eq/kg egg, 29.01 MJ eq/kg, 17.76 g SO ₂ eq/kg and 27.79 g PO ₄ eq/kg. Eggs on farms had the greatest environmental impact due to the supply of feed for laying hens (74.94%) and the use of natural resources (24.42%).
Arulnathan et al. (2022) [48], Canada	Internal causality in agri-food Life Cycle Assessments: Solving allocation problems based on feed energy utilization in egg production	⁴ The ME model was used to quantify the allocation rates of eggs and chickens slaughtered in different systems. The egg allocation rate is between 82.6% and 97.5%. The co-product of spent chickens can be allocated up to 25% for net energy.
Ershadi et al. (2021) [49], Canada	Comparative life cycle assessment of technologies and strategies to improve nitrogen use efficiency in egg supply chains	Strategies and Acid Scrubber provide ⁵ NUE improvement options (15% and 13%, respectively). These strategies reduce acidification (35% and 21%) and eutrophication potential (26% and 16%), but they increase other impacts, such as energy consumption and the depletion of the ozone layer.
Tsai et al. (2021) [50], USA	Life cycle assessment of cleaning-in-place operations in egg yolk powder production	The ⁶ LCA was used to quantify the impacts of the different stages in the manufacture of powdered egg yolk. The total result obtained was 1.71 kg CO ₂ eq.
Li et al. (2021) [51], Canada	Net zero energy barns for industrial egg production: An effective sustainable intensification strategy?	A facility with ⁷ NZE poultry housing infrastructure will provide environmental benefits over time. Lifecycle environmental impacts of eggs are 0.89–64.82% lower in the NZE shed.
Costantini et al. (2021) [52], Italy	Environmental sustainability assessment of poultry productions through life cycle approaches: A critical review	One hundred and fifty-five studies were imposed, of which forty-seven were reviewed. The agricultural phase weighs heavily on the impact of the finished food product. However, feed consumption and waste management are primarily responsible for the impacts generated.

Table 1. Cont.

Reference, Local	Article	Conclusions
Kanani et al. (2020) [53], Canada	Waste valorization technology options for the egg and broiler industries: A review and recommendations	⁶ LCA studies represent only 4% of the literature in this review. Currently, there is no link between the academic literature and the adoption of technologies for the valorization of poultry waste. Therefore, it is essential to carry out detailed studies (regionalized) to determine and understand the environmental resources and the waste generated.
Costantini et al. (2020) [54], Italy	Investigating on the environmental sustainability of animal products: The case of organic eggs	Feed supply is the main access point (49% to 87%) for all impact categories (1.56 kg CO ₂ eq/kg). The impact is less than that for conventional eggs.
Gunnarsson et al. (2020) [55], Sweden	Systematic Mapping of Research on Farm-Level Sustainability in Egg and Chicken Meat Production	The literature between the years 2000 and 2020 resulted in a mapping: only three articles covered the three dimensions of sustainability; ten addressed aspects of economic sustainability; eighteen addressed aspects of environmental sustainability; and twenty-three addressed aspects of social sustainability.
Oryschak et al. (2020) [56], Canada	Reconsidering the contribution of Canadian poultry production to anthropogenic greenhouse gas emissions: returning to an integrated crop–poultry production system paradigm	The carbon footprint is considered a discourse around climate change policy, but the exclusion of carbon fixation perpetuates a mistaken assumption that livestock is a net contributor to the ⁸ GHG emissions problem by replacing part of a solution.
Fritter et al. (2020) [57], Canada	A survey of Life Cycle Inventory database implementations and architectures and recommendations for new database initiatives	For the development of new ⁹ LCI database features, the format, nomenclatures, third-party providers, third-party initiatives and technical implementation are recommended.
Estrada-González et al. (2020) [19], Mexico	Decreasing the Environmental Impact in an Egg-Producing Farm through the Application of LCA and Lean Tools	The climate change category is a hotspot in egg production, with emissions of 5.58 kg CO ₂ eq/kg per egg produced.
van Hal et al. (2019) [58], Netherlands	Accounting for feed-food competition in environmental impact assessment: Towards a resource efficient food-system	Using ¹⁰ LCF economic allocation reduced ¹¹ GWP by 48–58%, ¹² EU by 21–37%, ¹³ LU by 34–47% and ¹⁴ LUR by 32%. Using ration-based allocation, the impact per kg of egg was further reduced by 54% for GWP, 38% for EU, 94% for LU and 88% for LUR.
Vetter et al. (2018) [59], United Kingdom	The potential to reduce GHG emissions in egg production using a GHG calculator—A Cool Farm Tool case study	The highest GHG ⁸ emissions come from feeding, followed by transport and manure management. The results show that the average GHG emissions decreased over the three years of the study by almost 25%.
Abín et al. (2018) [60], Spain	Environmental assessment of intensive egg production: A Spanish case study	Land use was the most prominent category, followed by terrestrial ecotoxicity and freshwater ecotoxicity. The carbon footprint of egg production was calculated to be 2.66 kgCO ₂ eq per dozen eggs.
Pelletier et al. (2018) [61], Canada	Sustainability in the Canadian Egg Industry—Learning from the Past, Navigating the Present, Planning for the Future Nathan	The challenges presented are aimed at egg producers. Acquiring practical knowledge, transitioning management and housing systems or not and analyzing the economic values of new systems, among other points, must be evaluated. This analysis can identify preferred paths, potential pitfalls and outstanding interdisciplinary research questions.

¹ FCR (Feed Conversion Ratio); ² MOS (Mannan Oligosaccharides); ³ SBM (Soybean Meal); ⁴ ME (Metabolizable Energy); ⁵ NUE (Nitrogen Use Efficiency); ⁶ LCA (Life Cycle Assessment); ⁷ NZE (Net Zero Energy); ⁸ GHG (Greenhouse Gas); ⁹ LCI (Life Cycle Inventory); ¹⁰ LCF (Low-Cost Feed); ¹¹ GWP (Global Warming Potential); ¹² EU (Energy Use); ¹³ LU (Land Use); ¹⁴ LUR (Land Use Ratio).

The studies presented in Table 1 predominantly highlight the relevance of the LCA and identify that the feeding of laying hens and the proper management of manure are the main contributors to the emission of greenhouse gases and impact the life cycle of the eggs. It was also possible to identify that these studies did not include the complete life cycle from the cradle to the retail of the eggs, only up to the pre-gate of production [20,43–50]. It should be noted that the most relevant impacts considered in the studies presented in Table 1 were: Acidification (kg SO₂ eq.), Eutrophication (kg N eq.), Fossil Fuel Depletion (MJ surplus), Global Warming Potential (kg CO₂ eq.), Ozone Depletion (kg CFC-11 eq.) and Ecotoxicity CTUe (comparative toxic unit equivalents).

The studies proposed by Cederberg et al. [62], Pelletier et al. [63] and Pelletier [42] analyzed the advances in egg production between the years 1990 and 2005 (Switzerland), 1960 and 2010 (USA) and 1962 and 2012 (Canada), respectively, through LCA. As a positive effect, it was found that, over the years, the footprint has been reduced, that is, the impacts on the environment in the production system are being rethought.

The Brazilian studies that are closest to the objectives proposed in this review are the references by Silva et al. (2014) [64] and Fernandes (2020) [65]. The authors [64] compared the environmental burden of two small-scale and large-scale broiler production systems in Brazil and two in France. The author [55] analyzed the environmental sustainability of different egg production environments. The research focused on analyzing the ambience of open, closed and alternative external warehouses.

In Brazil, there is also no specific norm for the intensive production of fresh eggs, but the intensive egg production system undergoes constant changes. The ABNT (Brazilian Association of Technical Standards) [52] considers only NBR 16437: 2016 Poultry—Production, classification and identification of free-range egg [53], paying attention only to the semi-extensive production of free-range eggs. Because it is an intensive production system with growing demand, studies are needed that clearly and accurately indicate the current impact of egg production on the environment, as every production process generates the depletion of natural resources, material flows, the cost of energy and increased emissions along the production chain [18].

3.1. Life Cycle Assessment Methods

According to Horne et al. [66], when defining the scope of the LCA, the limits of the system are determined, with the identification of the entire production process. Figure 3 illustrates the flow diagram of the egg production system.

The system boundaries for a study include all relevant material, energy and emission flows linked to all processes in the cradle-to-farm egg supply chain. This includes breeder, hatchery, pullet and layer facilities. As this is a start-to-finish assessment of the farm gate environmental life cycle (i.e., study of the environmental footprint) of conventional egg production, it is worth noting that the use/reuse/maintenance part will not be considered, since this is the “post-gate” analysis. This assessment of the life cycle of the egg production system does not consider the “post-gate” analysis [67]. Figure 4 represents the limits of the Life Cycle Assessment system for Egg Production, according to Turner et al. [44].

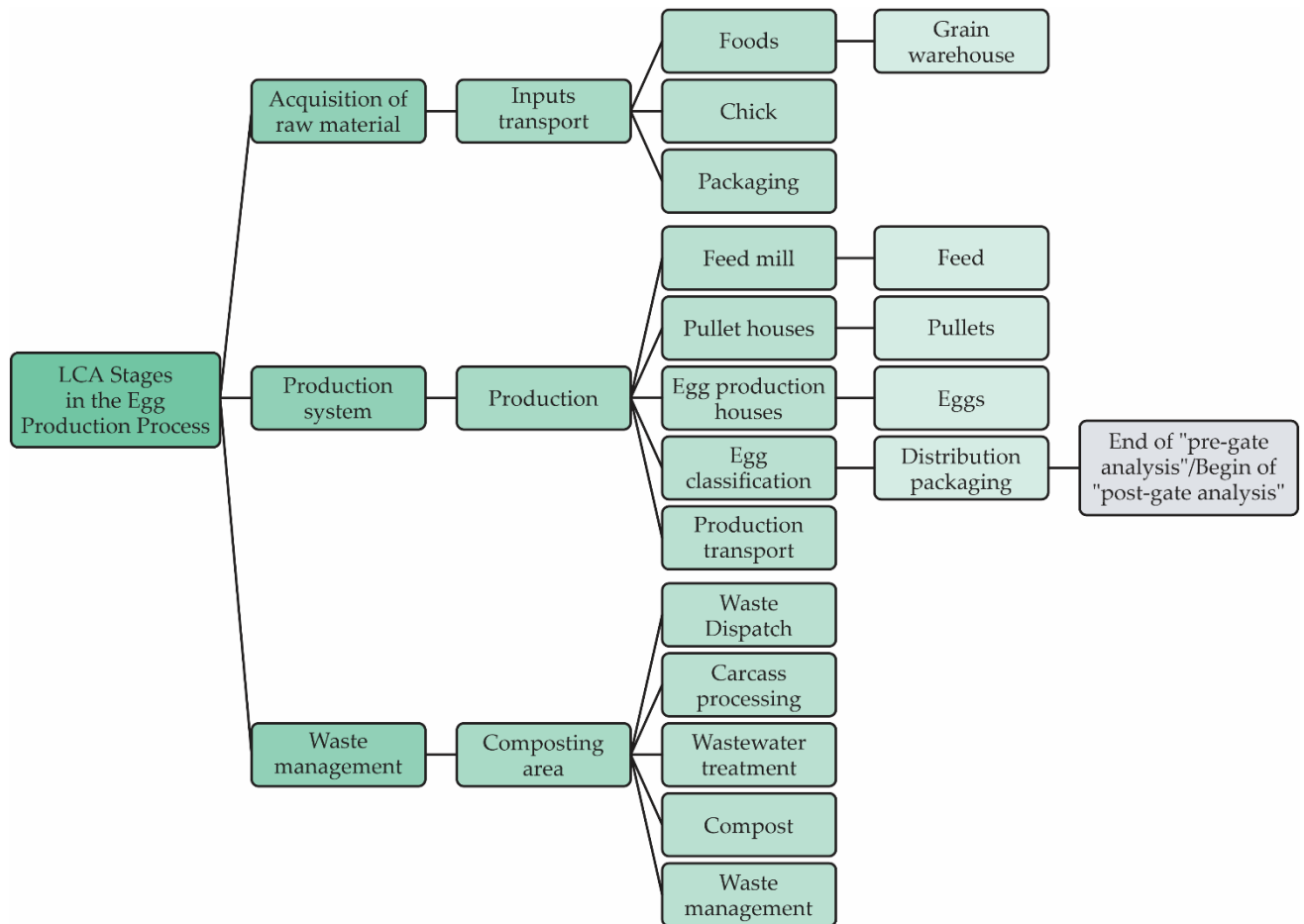


Figure 3. Flow diagram of the egg production system.

It is worth mentioning that transports between processes are also considered. The most used functional unit is the ton of eggs per unit of time. The functional unit and the limits of the system can be chosen as long as they are in agreement with the comparisons between the results [42]. Every unit involved in the production system must be included, as well as all component inputs and outputs, such as emissions and waste produced [40]. The analysis also does not include inputs and emissions associated with the production and maintenance of infrastructure, such as machinery and buildings. They typically make trivial contributions to the supply chain [42]. Figure 5 summarizes the Inputs/Outputs of the Egg Production Process, along with their respective (assigned) units. It is important to emphasize that this information is not immutable, showing only a suggestion of relevant inputs/outputs.

Midpoint impact categories and category indicators are employed in the impact assessment phase of the life cycle. Pelletier et al. [42] describe the impact categories in their study of LCA in the egg production system, considering the following as impact categories: Global warming (CO₂ equivalence), acidification (SO₂ equivalence) and eutrophication (PO₄ equivalence), cumulative energy demand and water and land use.

It is important to highlight that the impact categories do not follow a specification and may vary according to the assessment carried out.

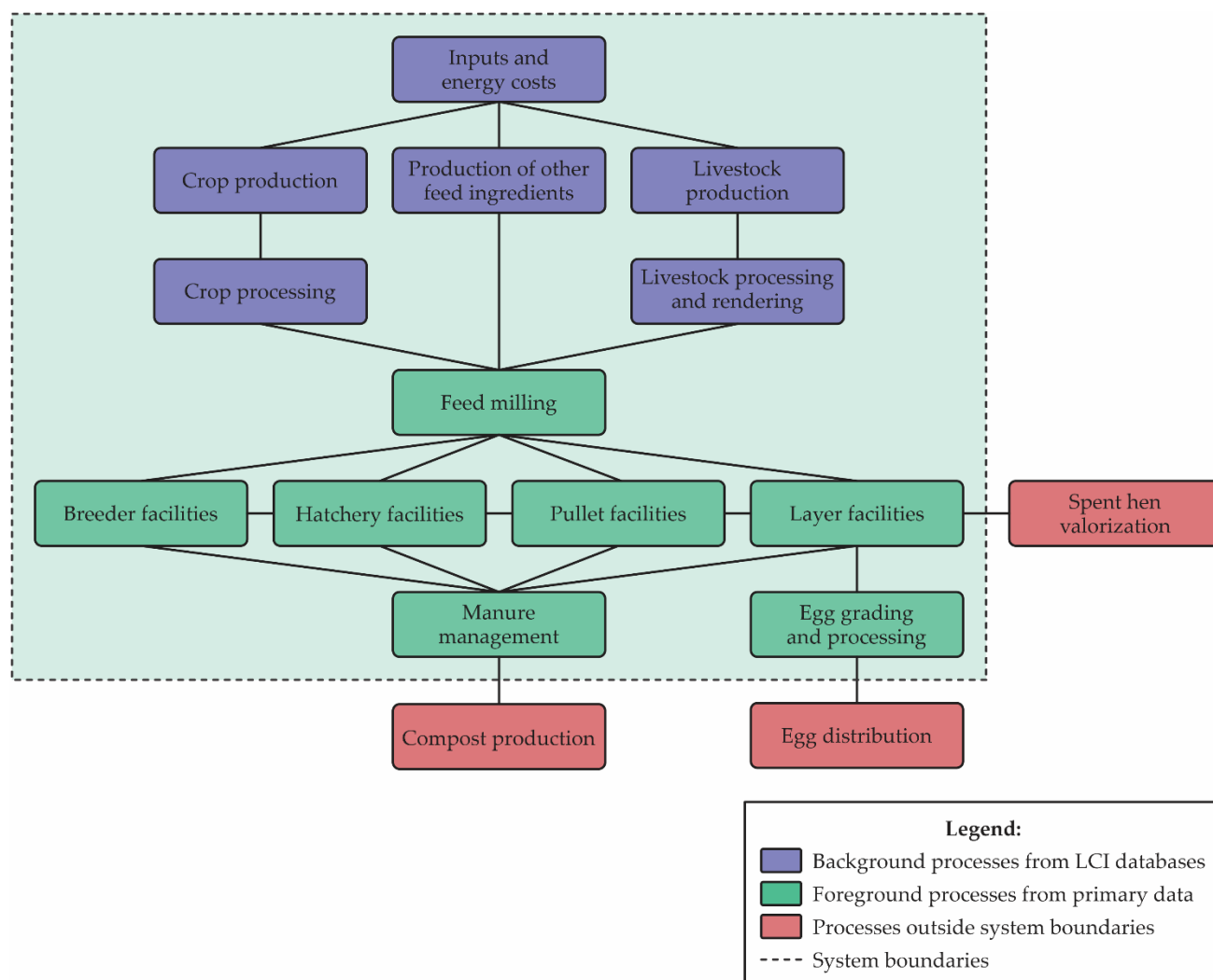


Figure 4. Limits of the egg production Life Cycle Assessment system. Source: Turner et al. [44]—Adapted by the author.

Allocation is a common strategy for solving multifunctionality problems in LCA, but the ISO 14040 and 14044:2006 [21,22] standard requires interpretations that are difficult to implement in practice. According to Pelletier et al. [58], three divisions may favor the allocation of an LCA, namely: the consequence and attributes of international data modeling approaches; adherence to a natural science-based approach; and, finally, a socioeconomic approach. The allocation of co-products is defined as products used in another economic activity. Unproductive chickens, for example, can be consumed (human food) or processed for animal feed, thus being destined. When they are not destined, they are sent for incineration and composting, being only discarded [57].

The choice of allocation methods is the target of criticism in LCA studies. Studies need to indicate how allocation systems are modeled, including which allocation procedure will be applied. The methods generally chosen by practitioners are economic allocations (based on economic value) and bulk allocations (based on reference weight or volume). The allocation factors are represented by the value of the product considered (according to the allocation unit chosen) and by the total value of the products considered in the system [68].

INPUTS			Egg production	OUTPUTS				
Description		Unity		Description		Unity		
Information on the origin/destination of all these materials	Number of chicks	unitary		Eggs	unitary			
	Surface water consumption	m ³		Spent hens	tonne			
	Underground water consumption	m ³		Waste: Wastewater Sanitary Sewage Municipal garbage (collected) Manure (used as fertilizer) Dead laying hens	m ³ m ³ tonne tonne tonne			
	Concessionaire energy consumption	kWh						
	Generations energy consumption	kWh						
	Cleaning products	tonne						
	Feed production: Corn Soy Bone meal Salt Limestone Among other input	tonne tonne tonne tonne tonne tonne						
	Packing material: Carbboard Plastic Among other input	tonne tonne tonne		tonne tonne tonne	Atmospheric emissions: NH ₃ CH ₄ CO ₂ SO ₂ CFC Particulate material Among other inputs	tonne tonne tonne tonne tonne tonne		
							Transport: Vehicles (forklift, cars and trucks) Diesel fuel Gasoline fuel LPG fuel	km liters liters kg

Figure 5. Input and Output analysis in the Egg Production Process (just a suggestion of relevant inputs/outputs).

3.2. Life Cycle Assessment Analysis

An essential element in LCA practice is the distinction between foreground data and background data. Foreground data are considered the data of primary concern, and background data are delivered to the foreground system as aggregated datasets, where operations are not identified [27]. Foreground data for egg production are usually collected from the producer's database. The corresponding values can also be considered as weighted averages of production (calculated values). Background system data will be required for integration with inventory data but modified where possible for Brazilian conditions.

As per ISO 14040 and 14044:2006 [21,22], data quality was assessed for foreground processes (i.e., egg production and layer manure management) as well as background processes. Bamber et al. [69] concluded that less than 20% of the LCA studies published between the years 2014 to 2018 reported any type of uncertainty analysis. Parameter uncertainty (i.e., uncertainty in inventory data) is most frequently reported, with 82% of studies, although other sources of uncertainty are considered equally important. Monte Carlo analysis was the most popular method, with 301 publications (61%) using it to propagate uncertainty results regardless of the LCA type.

3.3. Impact Assessment Methodologies

Currently, there are a considerable amount of software, developed by research centers, universities and companies around the world, that help in the development and execution of the LCA of different products and services. These

computer programs facilitate the manipulation of the large and varied amount of data that an LCA requires. Table 2 lists some of the LCA software available on the market. It is important to emphasize that these are just a selection of software, and other software may be available.

Table 2. Software available for life cycle assessment, indicating providers and countries where they were developed (only software suggestions).

Tools	Provider	Country
SimaPro [70]	Pré-Sustainability	Netherlands
OpenLCA [71]	GreenDelta	Germany
GaBi [72]	Sphera	Germany
Umberto [73]	IPoint	Germany
Ecodesign Studio [74]	Altermaker	France
Air.e LCA [75]	Solidforest	Spain
ECOSPEED Scout [76]	ECOSPEED Climate Software Solution	Switzerland
EarthSmart [77]	EarthShift Global	USA
Ecodex [78]	Selerant	USA
PLACES [79]	The Circulate Initiative	USA
LCA4Waste [80]	ETH Zurich	Switzerland
GREET [81]	Argonne National Laboratory	USA
KCL-ECO [82]	KCL Piloting Knowledge	Finland
Sustell [83]	DSM	Netherlands

OpenLCA [71] is an open-source software for Life Cycle Assessment (LCA) and Sustainability, developed in 2006 by GreenDelta [31]. The software is considered to be a data integrator that integrates the databases available from providers and networks. The Ecoinvent Life Cycle Impact Assessment (LCIA) set of methods is available through the openLCA Nexus [30]. Networks such as OpenLCA Nexus and the Ecoinvent database (versions 2.2 to 3.6) are identified as possible solutions to the impacts generated in production, allowing for the greater distribution and interoperability of data for life cycle assessments [74].

Developed by DSM animal nutrition and production experts [75], the Sustell Intelligence Platform [73] is a tool for the data entry, measurement and visualization of end-to-end results on environmental footprint. Based on a complete LCA, the software's precise calculation allows for tangible and measurable improvements, from agricultural feed production to the final product such as broilers, dairy products, laying hens and pig fattening. The Sustell software provides data transparently to the producer, with the main objective of reducing the environmental footprint of a farm.

3.4. Life Cycle Interpretation

The life cycle assessment and interpretation analyses described by ISO 14040 and 14044:2006 [21,22] and recommended by UNEP/SETAC (United Nations Environment Program/Society for Environmental Toxicology and Chemistry) [19] result in criteria for three areas of protection: human health, ecosystem quality and natural resources. The definition of these areas aims to safeguard the values considered important for society. Based on the entire review presented here, it was possible to identify the main environmental impacts caused by egg production.

Along with calculations of the lifecycle environmental impacts of egg production, the authors [17,32,44,48,49] describe how a contribution analysis can determine impact hotspots across the entire egg production chain. It was also possible to define the expected critical points, with the feed and manure production processes being the most critical. The identification of hotspots can

provide valuable information for industries and egg producers to provide targeted strategies for reducing the environmental impacts of egg production systems [58]. However, the LCA studies conclude their evaluation with precise, transparent and globally recognized results, resulting in the provision of the total environmental footprint (Kg CO₂ eq) per product unit.

Recent studies (2022) on the assessment of the life cycle impacts of egg production in the European Union [74] have analyzed the four laying systems, namely: enriched cages, barns, free range and organic. The authors state that the composition of the feed and the handling of the manure are the factors that directly affect the total environmental impact of the eggs, regardless of the posture system adopted. They also conclude that organic eggs have more significant environmental impacts than conventionally produced eggs, due to the adaptation of laying hen diets. In the same year [44], contemporary Canadian egg production systems were evaluated during the transition from conventional cages to alternative housing systems. Feed formulations and different management systems between caged and cage-free pullet production systems were the main contributors to environmental impacts. The results indicated that conventional caged methods outperform other productions and that the transition from traditional cages can be negative for the environmental sustainability of Canadian egg production.

It is important to emphasize that all the studies presented in this review are not the only or exclusive ways to perform an LCA of a product or process. All studies generally provide an assessment guideline to better understand and address the impacts generated throughout its life cycle, along with the need to consider issues related to climate change and biodiversity, from a holistic perspective [84].

4. Conclusions

This review presents, in general terms, the Life Cycle Environmental Assessment (according to ISO 14040 and 14044:2006) [21,22] of an egg-producing farm, from cradle to gate, and the tools available for this purpose. The studies presented predominantly highlighted the relevance of LCA and identified that the feeding of laying hens and the proper management of management are the main contributors to the emission of greenhouse gases and other negative impacts on the environment in the life cycle of the eggs. These studies did not include the complete life cycle from the cradle to egg retail. Although chicken eggs are consumed worldwide as a valuable and inexpensive source of protein, there is an obvious lack of studies on the environmental performance of production. Brazil is considered a productive country but is in development. For this reason, most references addressed are international, which often does not match the Brazilian reality. A data gap was identified regarding accounting for inputs such as energy flows and natural resources, data on sustainability in different egg production systems (conventional and alternative) and the impact of each of these systems on the environment. One of the biggest challenges for researchers and producers is to obtain incentives for the use of flexible and transparent tools that can clearly and transparently translate their environmental footprint. In addition, it is expected that the references given as results will be useful in expressing future discussions about the impacts on each stage of the egg production chain.

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Management of laying hen manure in intensive composting with windrows: Modeling emissions of N, P and CH₄

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Abstract

The facilities or areas designated for composting laying hen manure are crucial structures within egg production systems. Due to the high concentration of gases present, proper management, and control of emissions from the manure are essential actions to mitigate potential damages and ensure the operational safety of the system. Therefore, the objective of this study was to quantify nitrogen emissions, including nitrous oxide (N₂O), nitrate (NO₃), nitric oxide (NO_x), and ammonia (NH₃), methane (CH₄) emissions, and phosphorus (P) losses from laying hen manure in a semi-open composting area of an egg-producing farm. The values related to manure production, considered as input data, were provided by the farm. The values related to composting gas emissions were calculated using the guidelines of the IPCC (Intergovernmental Panel on Climate Change) for national greenhouse gas inventories. The results were calculated considering the annual production and the functional unit of 1000 hens produced in the rearing facilities and one ton of eggs produced in the laying facilities. With results of 4.85 kg N₂O, 68.45 kg NO₃, 48.92 kg NH₃, 12.00 kg NO_x, 27.01 kg CH₄, and 3.56 kg P₂O₅ per 1000 units of hens produced in cages; and 1.99 kg N₂O, 31.91 kg NO₃, 22.42 kg NH₃, 5.50 kg NO_x, 3.18 kg CH₄, and 1.21 kg P₂O₅ per ton of eggs produced, it was possible to conduct the inventory of emissions contributing to the manure management inventory of egg production in the intensive cage system.

Keywords: IPCC Guidelines; Inventory; Gases; Greenhouse Effect; Environmental Impacts; Life Cycle Assessment.

1. Introduction

According to the annual estimates of greenhouse gas emissions in Brazil, as presented by the Ministry of Science, Technology, and Innovations (MCTI) (Brasil 2022), atmospheric emissions from the LULUCF (Land Use, Land-Use Change, and Forestry), Agricultural, and Energy sectors make up 38.0%, 28.5%, and 23.2% of the total emissions, respectively. Followed by the IPPU sector (Industrial Processes and Product Use) with 6.1%, and Manure with 4.2%.

According to the Fourth National Inventory of Anthropogenic Greenhouse Gas Emissions and Removals (Fontana et al. 2021), the Agricultural sector is subdivided into seven sub-sectors following the IPCC methodology (Penman et al. 2006). From the total emissions of this sector, 57% correspond to Enteric Fermentation, 31% to

Managed Soils, 5% to Manure Management, 4% to Liming, 2% to Rice Cultivation, 0.9% to Urea Application, and 0.1% to Agricultural Residue Burning.

Although manure management accounts for 5% of the total emissions in the agricultural sector, the livestock sector, in particular, has been the focus of studies regarding the potential for climate change mitigation and the description of adaptation practices (Godde et al. 2021). This emphasis is due to the high global warming potentials of nitrous oxide (N_2O) and methane (CH_4), both originated from manure, which have considerably higher potentials than carbon dioxide (CO_2) emissions. The N_2O has a pollution potential 298 times higher than CO_2 , and CH_4 has a potential 25 times higher than CO_2 (deRichter and Caillol 2011). However, the emissions of N_2O and CH_4 coming from the manure of cattle and pigs occur in a much larger proportion compared to the manure from laying hens (Brasil 2020).

In recent decades, the egg industry has undergone significant changes to address the increasing demand for protein-rich food that is safe, accessible, affordable, and of high quality for the growing global population. Nevertheless, it is evident that future challenges are needed, as well as the production of meats such as beef, pork, or chicken (Pelletier et al. 2018).

Previous studies (Abín et al. 2018; Costantini et al. 2020; Dekker et al. 2011, 2013; Estrada-González et al. 2020; Guillaume et al. 2022; Pelletier 2017b, 2018; Pelletier et al. 2014; Salami et al. 2022; Taylor et al. 2014; Turner et al. 2022) indicate that feed production and manure management are the main enablers of the environmental impacts in the life cycle of egg production systems. Most research conducted so far, has been concentrated on enhancing feed efficiency by implementing balanced diets designed to maximize the utilization of crude protein (CP) in the feed and minimize its excretion, which contributes to the reduction of impacts generated in the composting area without causing nutritional losses in poultry (Maciel et al. 2023; Rostagno et al. 2017).

According to Nahm (2007), reducing CP levels and incorporating amino acids can lead to lower feed costs and a measurable reduction in nitrogen (N) content in bird manure. However, approximately 70-75% of the consumed N is lost or excreted, along with potential inefficiencies in digestion directly linked to significant N losses (Parsons, 1995). Still, bird manure is regarded as a valuable soil fertilizer, abundant in macro and micronutrients, particularly nitrogen, derived from hens fed balanced and concentrated diets (Figueroa et al. 2012; Stephenson et al. 1990).

The nitrification, denitrification, nitric oxide formation, nitrate leaching, and volatilization are considered to be the transformation process of N (Mendes et al. 2012). Gas emissions of N_2O occur through the processes of nitrification and denitrification in manure storages, with ammonia (NH_3) present in the slurry and fresh solid manure, through N excretion (Sousa et al. 2016). The decomposition of urea and uric acid present in bird manure is the primary source of NH_3 , representing about 50% of the proteins undigested by the hens (Oliveira et al. 2021). The CH_4 gas emissions occur in the anaerobic decomposition process of fecal organic matter in the manure storage facilities (Chadwick et al. 2011).

Losses of nutrients, both to surface water and/or soil infiltration, as well as to the air, can occur from manure storage systems, composting areas, and their application to agricultural fields as nutrient sources. Laying hen manure, due to its high concentration of N from formulated diets, contains elevated amounts of minerals, particularly calcium and phosphorus (P), in comparison to broiler manure. This leads to a more concentrated manure than poultry litter (Campos et al. 2017).

Composting is one of the primary treatment processes for laying hen manure. It is a biotechnological process involving the decomposition of organic matter under controlled aerobic conditions. While composting can occur

naturally, it is often enhanced by human interventions, such as turning windrows, which facilitate oxygenation and enhance efficiency (Augusto and Kunz 2011).

A composting system is considered a low-cost manure treatment method compared to other approaches, as it involves utilizing and managing shed manure along with the addition of low-moisture and economically valuable materials such as sawdust, straw, wood chips, among others. According to Pereira Neto and Stentiford (1992), this treatment process offers greater operational flexibility by combining low operating costs with high environmental efficiency, attributed to the control of production system manure. However, being a purely microbiological process, its efficiency relies directly on the action of microorganisms under favorable conditions such as temperature, humidity, aeration, organic compounds, carbon/nitrogen (C/N) ratio, material particle size, and windrow dimensions (Valente et al. 2009). Therefore, conventional aerated windrow processes are viable disposal options that yield marketable products.

Due to the intensive cage production system, characterized by high stocking densities of laying hens (pullets and hens) and the subsequent accumulation of manure, it has become a significant environmental concern (Augusto et al. 2009). Issues in the management of laying hen manure are linked to impacts on human and animal health, the generation of odors, nitrate leaching into the soil, and the eutrophication of water bodies, resulting into contamination of air, water, and soil (Gerber et al. 2007). Therefore, it is imperative to explore viable alternatives to quantify, reduce, and control these impacts.

Improving manure management requires identifying types of emissions and nutrient losses, along with quantifying their magnitudes (Giltrap et al. 2010). While there are measurements of nutrient losses and gas emissions in manure management, *on-site* measurements may be considered impractical due to various spatial and temporal factors. Congreves et al. (2016) claim that measurements are essential for developing inventories and management practices, but they can become costly, labor-intensive, and ineffective due to variables linked to climate, soil properties, and agricultural management. Thus, the use of models for estimating emissions and nutrient losses is widely employed to generate inventories when there are no actual measurements.

Consequently, given the absence of data regarding emissions from the composting area, the objective of this study is to quantify nitrogen emissions, including N_2O , NO_3 , NO_x , and NH_3 , CH_4 emissions, and phosphorus (P) losses from laying hen manure. The goal is to facilitate emission modeling as part of an inventory for manure management at an egg-producing farm in an intensive cage production system.

2. Material and methods

2.1. Model selection

To enhance the understanding of how nutrient losses and emissions from manure management are modeled, a literature review of Life Cycle Assessment (LCA) studies investigating egg production systems was conducted. A total of 21 sources were reviewed to assess their modeling methodology, specifically focusing on losses and emissions of nitrogen, phosphorus, and methane, as presented in Table 1. The results obtained from this review were used to report the choices regarding methods for modeling nutrient losses and emissions in this study (Pelletier 2017).

Table 1. Life Cycle Assessment (LCA) of egg production and its corresponding modeling of emissions/losses of N, CH₄, and P.

Source	N emissions/losses modeling approach	CH ₄ emissions modeling approach	P losses modeling approach
(Guillaume et al. 2022)	IPCC Tier 1	IPCC Tier 2	Santonja et, al. (2017)
(Turner et al. 2022)	IPCC Tier 1/2	IPCC Tier 1	Standardized rate
(Salami et al. 2022)	IPCC Tier 1/2	IPCC Tier 2	None listed
(Ershadi et al. 2021)	IPCC Tier 2	IPCC Tier 2	Dalgaard et al., 2008
(Nitschelm et al. 2021)	EMEP/EEA model, IPCC Tier 2	IPCC Nivel 2	SALCA-P
(Costantini et al. 2020)	IPCC Tier 1	IPCC Nivel 2	None listed
(Estrada-González et al. 2020)	None listed	None listed	None listed
(van Hal et al. 2019)	IPCC Tier 2	IPCC Tier 2	None listed
(Vetter et al. 2018)	IPCC Tier 1	IPCC Tier 1	None listed
(Abín et al. 2018)	PRTR model	PRTR model	None listed
(Pelletier et al. 2018)	IPCC Tier 1/2	IPCC Tier 1	Standardized rate
(Pelletier 2017)	IPCC Tier 1	IPCC Tier 1	Standardized rate
(Weeks et al. 2016)	Study-specific model	IPCC Tier 1	None listed
(Tayloret al. 2014)	IPCC Tier 1	IPCC Tier 1	None listed
(Pelletier et al. 2014)	IPCC Tier 1/2	IPCC Tier 1	Standardized rate
(Leinonen et al. 2014)	IPCC Tier 1/SUNDIAL	IPCC Tier 1	None listed
(Leinonen et al. 2013)	IPCC Tier 1/SUNDIAL	IPCC Tier 1	None listed
(Dekker et al. 2013)	IPCC Tier 1	None listed	None listed
(Weiss and Leip 2012)	CAPRI	CAPRI	None listed
(Leinonen et al. 2012a)	Study-specific model	Study-specific model	Study-specific model
(Dekker et al. 2011)	IPCC Tier 1	IPCC Tier 1	None listed

Source: Authors

Various emission models are employed to estimate nitrogen and methane emissions from poultry manure management processes. Most studies utilize IPCC Tier 1 or 2 methods, or a combination them, as outlined in Table 1. Tier 1 methods are the most general of IPCC methods, employing basic estimation equations based on a gain-loss approach, while Tier 2 methods are more complex, utilizing an empirical model and emission factors specific to each country (Gavrilova et al. 2019). Due to constraints and the availability of Brazilian data related to layer manure management, Tier 1 and 2 methods were employed, considering standard emission factors (Hergoualc'h et al.; Gavrilova et al. 2019), along with primary data obtained from the farm.

2.2. Percentage of Nutrients in Feed

The nutrient content in layer manure is related to the production system, the age of the hens, the quality and environment of the facilities, manure management practices, nutritional assessment of the hens, among other factors. Given these influencing factors, it becomes essential to quantify and characterize the nutrients present in the produced manure to ensure quality and safety in production (Maia et al. 2014).

Hens' manures typically have an average composition of 1.7 to 2.8% nitrogen (17 to 28 kg N/ton), 2.2 to 3.7% phosphorus pentoxide (22 to 37 kg P₂O₅/ton), and 1.2 to 1.7% potassium oxide (12 to 17 kg K₂O/ton) per ton of produced manure, among other micronutrients, coming from a balanced diet (Santinato et al. 2017). The quantities of nitrogen and phosphorus present in the excreta, the nutrients with higher concentrations, are calculated based on the nutrient composition of feed formulations and the hens' consumption levels (Pelletier 2017).

When calculating N and P excretion rates through a nutrient mass balance model, the proportions of N and P entering the systems (via feed) for the growth of hens and laying hens are determined, along with the proportion of these nutrients lost due to bird mortality. The quantities of N and P used for growth, production, and losses due to mortality are then subtracted from the inputs of N and P. It is presumed that the remaining amounts account for the excreted N and P (Pelletier 2017; Pelletier et al. 2014).

In Brazil, the formulation of feed for laying hens is guided by the Brazilian Tables for Poultry and Swine (Rostagno et al. 2017). These tables recommend that the feed provided to laying hens during the production cycle should contain a crude protein content ranging between 16.0% and 18.0%, depending on ambient temperature and age of the hens.

For the current study, the nutritional information of the feed composition provided by the farm was considered. The main ingredients included corn (7.2% crude protein, CP), soybean meal (48% CP), dried distillers' grains (DDG) (40% CP), soybean hulls (9.9% CP), and meat and bone meal (50% CP). On average, the total crude protein percentage varies from 18.5% to 16.7% in one ton of feed produced for hens and laying hens, respectively.

For the determination of %N, values were obtained and converted using the Kjeldahl Method, which considers the conversion factors of 5.65, 5.52, and 6.25 for the protein percentages of corn, soybean, and meat and bone meal, respectively (Purgatto 2016). Regarding the percentages of P, the compositional percentages of the feed ingredients were utilized, as per (De Filho et al. 2002; Talamini et al. 2022; Thiago and Silva 2001). Table 2 describes the approximate percentage of N and P based on the inputs present in each feed composition.

Table 2. Percentage approximation of food inputs used to estimate the calculation of nitrogen (N) and phosphorus (P) intake, excretion, and losses.

Feed ingredients	N (%)	P (%)
Maize grain	1.28	0.30
DDGs (Distiller's Dried Grains)	7.08	0.51
Meat and bone meal	8.00	6.45
Soybean meal	8.70	0.71
Soybean hulls	1.79	0.17

Source: Authors

The nutrient mass balance based on feed composition considers the compositions and nutritional levels for each type of feed. When considering the average feed consumption and the percentage of crude protein (CP) in its composition, the total nitrogen (Nt) value can be obtained by converting the mass of CP, dividing it by the value of 6.25 (Galvani and Gaertner 2006).

2.3. Volatile solids excreted and nitrogen excretion rate of laying hens

According to the IPCC methodology (Gavrilova et al. 2019), the rates of volatile solids excreted should be determined by production category, species, and age of the growing animal. The standard rates of volatile solids excretion (Tier 1) are presented in Table 10.13A, represented in Appendix A, in units of volatile solids excreted per 1000 kg of animal/day. These rates can also be applied to subcategories (Tier 2), such as stages of bird growth, using the typical animal mass (TAM), as per equation 1.

$$VS = VSrate * \frac{TAM}{1000} \quad (1)$$

Where: VS = mean excretion of volatile solids per head (kg VS animal⁻¹); VSrate = standard SV excretion rate, according with Table 10.13A, Appendix A. Considered value 9.3 (kg VS (1000 kg of animal mass)⁻¹ day⁻¹); and TAM = typical animal mass, (kg animal⁻¹).

Considering the related values and the average weight of the laying hen at 1.6 kg (provided by the farm), the value of 0.01488 kg VS/animal/day is obtained for laying hens.

The approach based on nitrogen excretion, for the purpose of calculating N₂O emission factors (direct and indirect), as well as volatilization and leaching factors, is presented in Table 10.19, as outlined in Appendix B, in units of nitrogen excreted per 1000 kg of animal per day. These rates can also be applied to subcategories (Tier 2), such as poultry growth stages, using the typical animal mass (TAM), as per Equation 2.

$$Nex = Nrate * \frac{TAM}{1000} \quad (2)$$

Where: Nex = average N excretion per head (kg N animal⁻¹); Nrate = Standard N excretion rate, according to Table 10.19, Appendix B. Considered value: 1.2; and TAM = typical animal mass, (kg animal⁻¹).

Considering the same previously mentioned values, the obtained value for laying hens is 0.001632 kg N/animal/day.

In accordance with the ASAE (American Society of Agricultural Engineers) standard on Waste Production and Characteristics (ASAE 2005), which characterizes combined urine and feces for various livestock, it is estimated

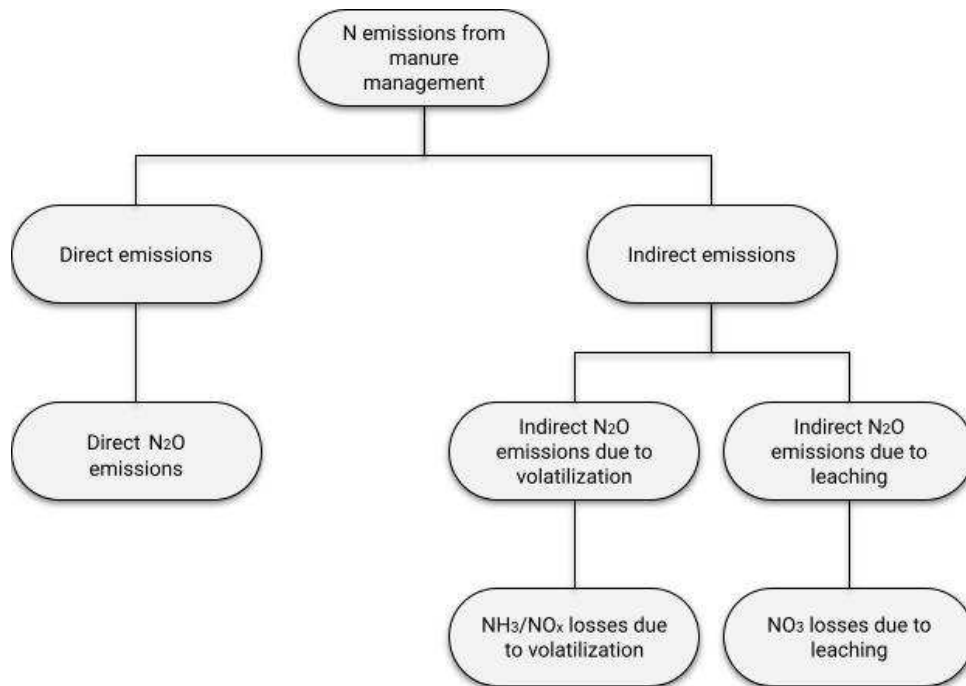
that each laying hen excretes around 0.088 kg of manure per day, with a moisture content of 75%, nitrogen content of 0.0016 kg/animal/day, and phosphorus content of 0.00048 kg/animal/day. França (2017), through practical experiments, assessed the nitrogen excretion by laying hens during the rearing and laying phases. It was stated that at daily temperatures between 20 and 25 °C, similar results to ASAE (2005) were found, considering a moisture content of 75%, and pH of 7.9 and 8.0, respectively.

Thus, it is emphasized that the typical estimated characteristics of combined urine and feces, based on the values estimated by the ASAE standard (2005), are consistent with the values estimated by the IPCC manure emissions and management report (Gavrilova et al. 2019), as well as the values obtained by the farm.

2.4. Estimate of nitrogen emissions and losses (N)

Figure 1 illustrates how the estimates of direct and indirect nitrogen emissions and losses were conducted during manure storage. The approach is based on nitrogen excretion, emission factors for N₂O emissions, as well as volatilization and leaching factors (Gavrilova et al. 2019).

Figure 1. Flowchart of nitrogen emissions and losses estimates in the management of manure from laying hens



Source: Authors

2.4.1. N₂O Emissions from Manure Management

The direct emissions of N₂O from manure management calculated according to the IPCC Tier 1 protocols, as per Equation 10.25 (Gavrilova et al. 2019), simplified in Equation 3.

$$kg \text{ direct } N_2O \text{ emissions} = kg \text{ N excreted} * EF_3 * \frac{44}{28} \quad (3)$$

It is emphasized that only a single species/category was used, without nitrogen input for anaerobic digestion systems. A weighted emission factor EF_3 (dimensionless in this context) is considered based on the farm's manure management systems. In this case, the "windrow composting" management system was considered. The value for the

standard emission factor for the windrow composting system is 0.005 (kg N₂O-N (kg N excreted)⁻¹), detailed in Appendix C.

The indirect emissions of N₂O can also be released from manure management systems through two main pathways: ammonia (NH₃) and nitrous oxide (NO_x) volatilization, and nitrate leaching. Nitrogen volatilization from laying hen manure management systems occurs in the form of NH₃ and NO_x. This volatilization is calculated according to Equation 10.26 (Gavrilova et al. 2019), simplified in Equation 4.

$$kg N_{volatiz. como NH_3 e NO_x} = kg N_{excreted} * Frac_{GASM1} \quad (4)$$

Where: Frac_{GASM1} is the default value of 0.21 (kg NH₃-N+NO_x-N (kg N)⁻¹) applied or deposited, according to IPCC (Hergoualc'h et al. 2019), Table 11.3, detailed in Appendix D. This value represents the volatilization of all applied organic nitrogenous fertilizers.

The indirect emissions of N₂O from volatilized NH₃ and NO_x are subsequently calculated according to IPCC (Gavrilova et al. 2019), Equation 10.28, simplified in Equation 5.

$$kg indirect N_2O emissions = kg N_{volatized as NH_3 and NO_x} * EF_4 * \frac{44}{28} \quad (5)$$

Where: EF₄ is the default value of 0.01 (kg N₂O-N (kg NH₃-N + NO_x-N volatilized)⁻¹), according to IPCC (Hergoualc'h et al. 2019), Table 11.3, detailed in Appendix D.

As indirect N₂O emissions from nitrate leaching are calculated according to Equations 10.27 and 10.29 (Gavrilova et al. 2019). Firstly, Equation 10.27 is used to calculate the amount of N lost through leaching, simplified in Equation 6.

$$kg N_{leached} = kg N_{excreted} * Frac_{Leach} \quad (6)$$

Where: Frac_{Leach} represents the fraction of N that is leached from the manure management system. A default value of 0.24 kg N kg⁻¹ of N additions or depositions from grazing animals is used for Frac_{Leach}, as per Table 11.3, detailed in Appendix D.

The indirect emissions of N₂O from the leached fraction are subsequently calculated according to Equation 10.29 (Gavrilova et al. 2019), simplified in Equation 7.

$$kg indirect N_2O emissions_{leachate} = kg N_{leached} * EF_5 * \frac{44}{28} \quad (7)$$

Where: EF₅ is the default value of 0.011 (kg N₂O-N (kg N)⁻¹), representing the proportion of liquid and solid manure management systems indicated in the collected data, as per Table 11.3, detailed in Appendix D.

2.4.2. Nitrogen emissions from the application of manure to agricultural soils

Similar to the estimates of direct and indirect nitrogen emissions and losses during manure storage, the estimates of nitrogen emissions from the application of manure to agricultural soils are also considered. The approach is based on N₂O emission factors, as well as volatilization and leaching factors (Hergoualc'h et al. 2019). To calculate the portion of N applied to the fields, the total N losses from manure management systems are subtracted from the total excreted N, as calculated earlier using nutrient mass balances. All N emissions to agricultural soils are calculated according to IPCC Tier 1 protocols (Hergoualc'h et al. 2019), using standard emission factors. The direct emissions of N₂O are calculated according to Equation 11.1 (Hergoualc'h et al. 2019), simplified in Equation 8.

$$\text{Direct } N_2O \text{ emissions} = \text{kg N applied to field} * EF_4 \quad (8)$$

Where: EF_4 is the default value of 0.01 (kg N₂O-N (kg NH₃-N + NO_x-N volatilized)⁻¹), as per Table 11.3, detailed in Appendix D.

Additional nitrogen emissions can also be released through the volatilization of manure applied to the soil in the forms of NH₃ and NO_x, with additional indirect emissions of N₂O released from the volatilized fraction. The volatilized NH₃ and NO_x emissions from manure applied to the soil are calculated according to Equation 11.9 (Hergoualc'h et al. 2019), simplified in Equation 9.

$$\text{kg indirect } N_2O \text{ emissions}_{\text{volatilized}} = \text{kg N applied to fields} * \text{Frac}_{\text{gasm}} * EF_4 \quad (9)$$

Where: $\text{Frac}_{\text{GASM}}$ is equal to the default value of 0.21 (kg NH₃ -N + NO_x -N (kg N applied or deposited)⁻¹; and EF_4 is equal to the default value of 0.01 (kg N₂O-N (kg NH₃-N + NO_x-N volatilized)⁻¹, as per Table 11.3, detailed in Appendix D.

The indirect N₂O emissions from leaching and runoff after manure application are calculated according to Equation 11.10 (Hergoualc'h et al. 2019), simplified in Equation 10.

$$\text{Indirect } N_2O_{\text{leach}} = \text{kg N applied to field} * \text{Frac}_{\text{Leach}} * EF_5 \quad (10)$$

Where: $\text{Frac}_{\text{Leach}}$ is equal to the default value of 0.24 (kg N/kg N) additions or depositions from grazing animals; and EF_5 is equal to 0.011 (kg N₂O-N (kg N leached)⁻¹), a weighted emission factor representing the proportion of liquid and solid manure management systems indicated in the collected data, as per Table 11.3, detailed in Appendix D.

2.4.3. Methane (CH₄) emissions from manure management

Similar to the calculation of nitrogen emissions, the weighted emission factors are derived before the emission calculation, considering the proportions of different reported manure management systems. Methane (CH₄) emissions are then calculated according to the IPCC methodology, as per Equation 10.22 (Gavrilova et al. 2019), simplified in Equation 11.

$$\text{kg } CH_4 = \frac{[EF_7 * \text{volatile solids excreted}]}{1000} \quad (11)$$

Where: EF_7 is equal to 10.5 (g CH₄ (kg VS)⁻¹), a methane emission factor per animal category, based on the manure management system and climatic zone, as per Table 10.14, detailed in Appendix E.

The values related to volatile solids excreted were considered according to IPCC (Hergoualc'h et al.; Gavrilova et al. 2019), along with the annual quantity of manure produced by the farm, as presented in section 2.3. Currently, IPCC protocols do not include methods for estimating CH₄ emissions at the field level from N applications. Therefore, these emissions are excluded from the current analysis.

2.4.4. Phosphorus (P) losses from manure management

Different methods can be used to estimate P losses, ranging from the application of assumed loss rates to the estimation of losses using complex models. Oenema et al. (2007), through integrated modeling, concluded that 30% of excreted N was lost during storage; 19% through NH₃ emissions, 7% through NO, N₂O, and N₂ emissions, and 4% through leaching and runoff of N and P.

Studies on LCA (Pelletier 2017; Pelletier et al. 2014; Turner et al. 2022) consider a leaching rate of 2.9% according to the Danish mass balance model. Hussain et al. (2021) found that leaching rates vary between 3.5% and 7.2% kg P ha⁻¹ year⁻¹ depending on the cultivation system. Rittmann et al. (2011) consider that the two main phosphorus loss pathways are associated with soil erosion and leaching (46% of extracted P) and phosphorus in animal excretions (40% of extracted P). Piovesan (2006) states that the leaching process is more associated with soil physical conditions than with the quantities of deposited phosphorus.

In Brazil, most studies focus on evaluating nutrient losses through surface runoff, with pig and poultry manure being the main organic materials assessed. Peles (2007) evaluated P losses (kg ha⁻¹) in relation to the applied P in soluble and total forms, based on pig manure doses (m³ ha⁻¹), and obtained an average percentage of 2.48% P loss, with 4.49% being the highest P loss considered. According to Sharpley et al. (1994), phosphorus losses through surface runoff are generally less than 5% of the applied phosphorus, which aligns with the results presented by Peles (2007).

Abdala et al. (2012) assessed phosphorus saturation and leaching resulting from the application of chicken litter. However, the specific source of leached phosphorus could not be identified due to the low phosphorus content and the high soil adsorption capacity. Weathered soils in Brazil, known for their elevated phosphorus absorption capacity, exhibited no significant increase in leaching beyond the application rate. Consequently, it is suggested that future assessments should be more focused on examining the long-term relationship between soil properties and phosphorus loss, particularly under various soil conditions and manure management systems.

Given the absence of specific studies on phosphorus (P) losses through surface runoff and leaching in the Brazilian context, particularly in the management of laying hen manure, an approach involving the application of a standard loss rate was adopted. This method, following the works of Pelletier et al. (2014), Pelletier (2017), and Turner et al. (2022), assumed a P loss rate of 3.48%, reflecting the anticipated average losses in Brazil. It's worth noting that this calculated rate corresponds closely to the average rates reported by Rittmann et al. (2011), Piovesan (2006), and Peles (2007). Consequently, phosphorus losses are computed using Equation 12.

$$P \text{ emissions as } PO_4^{3-} = \frac{\text{Manure P content} * 0.03485}{0.3261} \quad (12)$$

Where: 0.3261 is a factor for the conversion of P to phosphate (PO_4^{3-}).

3. Results and discussion

When conducting the life cycle assessment of egg production in Brazil, the study quantified losses and emissions of nitrogen (N), phosphorus (P), and methane (CH₄) from the manure of both hens and laying hens. The analysis employed two functional units: one unit for the production of 1000 hens to evaluate the manure produced by hens, and another unit for the production of one ton of eggs to assess the manure produced by laying hens. The processes under evaluation encompassed the production of their respective outputs (hens and eggs) along with the concurrent generation of manure during production. Subsequently, this manure is treated as input data for the manure management process in the overall assessment.

The assessment of volatile solids excreted relied on values provided by IPCC (Hergoualc'h et al.; GavriloVA et al. 2019), and these were considered in conjunction with the annual quantity of manure produced by the farm. To calculate nitrogen excretion, a mass balance was executed, considering feed consumption and following the methodology proposed by ASAE (2005) and França (2017). Similarly, phosphorus excretion was determined through

a mass balance rooted in feed consumption. In estimating phosphorus losses, a value of 3.48% was assumed, representing the anticipated average losses in Brazil.

The percentages of nitrogen (N) and phosphorus (P) in the diets of hens and laying hens were computed using the nutritional composition of both formulations, as supplied by the farm. The calculated percentages for pullet diets were 18.5% crude protein (CP) and 0.6% phosphorus (P). For laying hen diets, the corresponding figures were 16.7% CP and 0.52% P.

The estimates of nitrogen emissions applied to the soils were derived by deducting the nitrogen emitted during manure management from the excreted nitrogen. The values for N₂O, NO₃, NH₃, NO_x, and CH₄ were calculated utilizing Tier 1 and 2 equations from the IPCC guidelines (Hergoualc'h et al.; Gavrilova et al. 2019). The detailed results for these emissions are presented in Tables 3 and 4, along with the corresponding phosphorus loss, in accordance with the specified functional unit.

Table 3. Calculation of nitrogen emissions, methane, and phosphorus losses, considering the functional unit of 1000 hens produced in cages.

Number of hens		1025.00
Excreted N (kg)		162.06
Excreted P(kg)		33.29
Estimates of nitrogen emissions		
	Description of emissions	Emission factor Emitted N
	Direct emissions of N ₂ O from manure management [(kg N ₂ O-N (kg N) ⁻¹]	0.005 1.27
	Volatilization of N as NH ₃ and NO _x [(kg NH ₃ -N + NO _x -N) (kg N) ⁻¹]	0.21 34.03
	Indirect emissions of N ₂ O due to NH ₃ /NO _x [(kg N ₂ O-N) (kg NH ₃ -N + NO _x -N) ⁻¹]	0.01 0.53
	Leaching of NO ₃ [kg N (kg N) ⁻¹]	0.24 38.89
	Indirect emissions of N ₂ O due to leaching [kg N ₂ O-N (kg N) ⁻¹]	0.011 0.67
	Direct emissions of N ₂ O after application to the soil [(kg N ₂ O-N (kg N) ⁻¹]	0.01 1.61
	Volatilization of N as NH ₃ and NO _x after ap. to the soil [(kg NH ₃ -N + NO _x -N) (kg N) ⁻¹]	0.21 26.89
	Indirect emissions of N ₂ O due to NH ₃ /NO _x volatil. [(kg N ₂ O-N) (kg NH ₃ -N + NO _x -N) ⁻¹]	0.01 0.34
	Leaching of NO ₃ in the soil [kg N (kg N) ⁻¹]	0.24 29.56
	Indirect emissions of N ₂ O due to leaching [kg N ₂ O-N (kg N) ⁻¹]	0.011 0.43
	Total N ₂ O (kg)	4.85
	Total NO ₃ (kg)	68.45
	Total NH ₃ (kg)	48.92
	Total NO _x (kg)	12.00
Estimates of methane emissions		
	Emissions description	Emission factor Emitted CH₄
	CH ₄ (kg)	10.5 27.01
Estimates of phosphorus losses		
	Emissions description	Emission factor Emitted P
	P ₂ O ₅ (kg)	0.03485 3.56

Table 4. Calculation of nitrogen emissions, methane, and phosphorus losses, considering the functional unit of one ton of eggs produced.

Number of hens	55.73
Excreted N (kg)	57.80
Lost P (kg)	11.36
Estimates of nitrogen emissions	
Emissions description	Emission factor Emitted N
Direct emissions of N ₂ O from manure management [(kg N ₂ O-N (kg N) ⁻¹]	0.005 0.45
Volatilization of N as NH ₃ and NO _x [(kg NH ₃ -N + NO _x -N) (kg N) ⁻¹]	0.21 12.14
Indirect emissions of N ₂ O due to NH ₃ /NO _x volat. [(kg N ₂ O-N) (kg NH ₃ -N + NO _x -N) ⁻¹]	0.01 0.19
Leaching of NO ₃ [kg N (kg N) ⁻¹]	0.24 13.87
Indirect emissions of N ₂ O due to leaching [kg N ₂ O-N (kg N) ⁻¹]	0.011 0.24
Direct emissions of N ₂ O after soil application [(kg N ₂ O-N (kg N) ⁻¹]	0.01 0.75
Volatilization of N as NH ₃ and NO _x after soil application [(kg NH ₃ -N + NO _x -N) (kg N) ⁻¹]	0.21 15.78
Indirect emissions of N ₂ O due to NH ₃ /NO _x volat. [(kg N ₂ O-N) (kg NH ₃ -N + NO _x -N) ⁻¹]	0.01 0.16
Leaching of NO ₃ in the soil [kg N (kg N) ⁻¹]	0.24 18.03
Indirect N ₂ O emissions due to leaching [(kg N ₂ O-N (kg N) ⁻¹]	0.011 0.20
Total N ₂ O (kg)	1.99
Total NO ₃ (kg)	31.91
Total NH ₃ (kg)	22.42
Total NO _x (kg)	5.50
Estimates of methane emissions	
Emissions description	Emissions factor Emitted CH₄
CH ₄ (kg)	10.5 3.18
Estimates of phosphorus emissions	
Emissions description	Emission factor Emitted P
P ₂ O ₅ (kg)	0.03485 1.21

3.1. Comparisons with other studies

Life Cycle Assessment (LCA) studies of egg production typically do not detail or specify the values considered for modeling emissions from manure management. However, they specify the adopted methodology, as presented in Table 1.

Among the cited authors, including Turner et al. (2022), Ershadi et al. (2021), Pelletier et al. (2018), Pelletier (2017), and Pelletier et al. (2014), the studies describe that nitrogen excretion was accounted for through the mass balance of feed consumption. The percentages of crude protein (CP) and phosphorus (P) were derived from research by Feedipedia, assuming values of 2.2% for N and 0.6% for P, corresponding to the chicken's body mass. Eggs were considered to contain 1.7% N and 0.21% P. These authors also consider phosphorus excretion through the mass balance of feed consumption, considering a 2.9% phosphorus runoff rate. The methane emission factor for laying hens is reported as 0.03 kg, and for chickens, it is 1.2 kg CH₄/head/year, with variations between dry and wet manure management systems.

Guillaume et al. (2022) similarly adopted the mass balance of feed consumption and utilized percentages of crude protein (CP) and phosphorus (P) from Feedipedia in their study. They incorporated the fraction of ingested

nitrogen retained in the body by laying hens as 0.3. Additionally, the phosphorus runoff rate to the soil was considered as 5%, and the methane emission factor was specified as 0.3 kg CH₄/head/year in the context of a dry manure management system.

In their respective studies, Costantini et al. (2020), Dekker et al. (2013), and Dekker et al. (2011) incorporated specific percentage values. Costantini et al. (2020), considered the following values: 0.1% for N₂O in the barn, 0.4% for N₂O outdoors, 1% for NH₃, and 1.1% for NO₃. On the other hand, the values utilized by Dekker et al. (2013) and Dekker et al. (2011) encompassed 2% for NO_x, 6% for NH₃, 2% for N₂O, and 0.4% for CH₄.

Abín et al. (2018) directly specifies the values considered in their studies according to the livestock sector in Spain (EPER-Spain), considering the values of 0.0318 kg NH₃, 0.007642 kg N₂O, and 0.08730 kg CH₄ per chicken/head/year.

Indeed, it is evident that authors present their emission modeling results based on their specific methodologies and the functional units they consider, when provided. The current study, like to the approaches of Turner et al. (2022), Ershadi et al. (2021), Pelletier et al. (2018), Pelletier (2017), Pelletier et al. (2014), and Guillaume et al. (2022), relies on the mass balance of feed consumption to determine the values of excreted nitrogen (N) and phosphorus (P). Notably, in this study, the percentages of crude protein (CP) and phosphorus considered align with the nutritional information sourced from the farm. The phosphorus runoff rate to the soil adheres to national references, and the emissions of NO₃, NH₃, NO_x, and CH₄ are computed using Tier 1 and 2 equations from the IPCC guidelines (Hergoualc'h et al.; GavriloVA et al. 2019), along with the annual quantity of manure produced by the farm.

3.2. Comparison with national data

The Agricultural Sector Reference Report on Manure Management (Picharillo et al. 2020), which contributed to the Fourth National Inventory of Anthropogenic Greenhouse Gas Emissions and Removals (Fontana et al. 2021), employed the IPCC 2006 methodology (Penman et al. 2006) using the Tier 1 method. It factored in the national population per head to calculate the total values of methane (CH₄) and nitrous oxide (N₂O) emissions. Table 5 juxtaposes the values assumed by the national inventory with the data derived from the current study.

Table 5. Estimation of CH₄ and N₂O Emissions as a Comparative Database.

Comparative Database	Animals	CH ₄ emissions (kg animal ⁻¹)	N ₂ O emissions (kg animal ⁻¹)
National inventory (2020) - ref. 2016	217878734	0.030	0.001
Production of 1000 Laying Hens	1025	0.026	0.002

* N₂O values disregarding soil application. Source: Fourth National Inventory of Anthropogenic Greenhouse Gas Emissions and Removals - Reference Report; The Authors.

When comparing the values obtained in the current study with the data presented in the national inventory, a variation of only 0.4% and 0.1% in CH₄ and N₂O emissions, respectively, is observed, indicating higher reliability of the considered data. It is worth noting that the National Emissions Inventory (Fontana et al. 2021; Picharillo et al. 2020), only considers egg production in the intensive cage system, similar to the present study, due to the predominance of this production system in Brazil (Silva 2019).

4. Additional considerations

Certainly, modeling emission systems poses a significant challenge in conducting a life cycle assessment (LCA) for a production system. In the present study, a combination of IPCC Tier 1 and 2 methods was employed to estimate nitrogen (N) and methane (CH₄) emissions, while a standardized loss rate was utilized to calculate phosphorus (P) losses from layer manure management. The use of models is often essential in estimating emissions for LCA due to measurement difficulties and limited access to new technologies. However, it is important to acknowledge that the use of models introduces a level of uncertainty into the proposed model. This uncertainty should be considered and communicated transparently in the assessment to ensure the reliability and robustness of the LCA results.

Indeed, both direct and indirect emissions play a significant role in contributing to environmental impacts, encompassing various aspects such as water and soil acidification, eutrophication of water bodies, impacts on human health, and biodiversity. The meticulous accounting of these emissions within the manure management system is crucial for a comprehensive assessment of the environmental impacts associated with the life cycle of poultry and other livestock production systems. A thorough consideration of these factors is essential for making informed decisions regarding the sustainability and environmental performance of such production systems.

The results obtained in this inventory will serve as a valuable contribution to the life cycle assessment (LCA) of egg production in the intensive cage system. The findings from this inventory will be integral in informing the manure management process within the broader LCA of egg production. Consequently, these values will play a crucial role in shaping the understanding of the environmental impacts associated with the production process of hens and eggs, where manure management processes are considered both as a final destination and as output data.

It's worth emphasizing the significance of this study for future research endeavors. For instance, the insights gained from this study can lay the groundwork for conducting a life cycle assessment of organic compost, which is identified as the second-largest product marketed by the farm. Such future research endeavors can further contribute to a holistic understanding of the environmental implications associated with various products and processes within the agricultural and livestock production sector.

5. Conclusion

After conducting an evaluation of the quantities of nitrogen (N) and phosphorus (P) present in the excreta, utilizing the mass balance approach and considering the nutrient percentage of the feed, the study successfully estimated the emissions of nitrogen (N), methane (CH₄), and phosphorus (P) losses from manure management. The results were calculated based on the annual production and the functional unit of 1000 hens produced by the rearing facilities and one ton of eggs produced by the laying facilities. The estimated values per 1000 hens produced in cages include 4.85 kg of N₂O, 68.45 kg of NO₃, 48.92 kg of NH₃, 12.00 kg of NO_x, 27.01 kg of CH₄, and 3.56 kg of P₂O₅. Similarly, the values per ton of eggs produced are 1.99 kg of N₂O, 31.91 kg of NO₃, 22.42 kg of NH₃, 5.50 kg of NO_x, 3.18 kg of CH₄, and 1.21 kg of P₂O₅. These estimated values will serve as crucial input data for the manure management inventory in the life cycle assessment (LCA) of egg production in the intensive cage system. They contribute to a comprehensive understanding of the environmental impact associated with manure management processes within the poultry production system.

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Ethical Approval

Not applicable.

Consent to participate

All authors whose names appear on the submission have agreed.

Consent for publication

All authors agreed with the content, and all gave explicit consent to submit before the work is submitted.

Author contribution

Conceptualization, F.d.F.M., I.d.F.F.T., R.S.G., N.P.; writing—original draft preparation, F.d.F.M.; writing-review and editing, N.S.R., F.C.d.S., M.A.I.-B., C.E.A.O.; L.F.d.S; supervision, I.d.F.F.T., N.P. and R.S.G. All authors have read and agreed to the published version of the manuscript.

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Competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A – Table 10.13A: Default values for volatile solids excretion rate (VS), according to IPCC (2019)

Values corresponding to the Latin American standard for volatile solids excretion rate, considering laying hens aged over one year.

TABLE 10.13A (NEW)																			
DEFAULT VALUES FOR VOLATILE SOLID EXCRETION RATE (KG VS (1000 KG ANIMAL MASS)-1 DAY ⁻¹)																			
Category of animal	Region				Latin America			Africa ⁶			Middle East ⁶			Asia			India sub-continent		
	North America	Western Europe	Eastern Europe	Oceania ⁷	Mean	High PS ¹	Low PS ¹	Mean	High PS	Low PS	Mean	High PS	Low PS	Mean	High PS	Low PS	Mean	High PS	Low PS
	Dairy cattle ⁴	9.3	7.5	6.7	6.0	7.9	9.0	7.1	18.2	21.7	15.2	10.7	8.4	11.8	9.0	8.1	9.2	14.1	9.1
Other cattle ⁴	7.6	5.7	7.6	8.7	8.5	8.1	8.6	12.0	10.2	12.7	14.1	10.5	16.8	9.8	6.8	10.8	12.2	13.5	12.0
Buffalo ⁴	NA	7.7	6.2	NA	11.2	NE		12.9	NE		9.8	NE		13.5	NE			NE	
Swine ³	3.3	4.5	4.0	4.0	5.0	3.3	8.3	7.2	4.3	8.7	4.3	3.9	7.2	5.8	4.3	7.1	7.7	5.5	8.7
Finishing	3.9	5.3	4.9	5.6	6.4	4.3	10.0	8.2	5.3	9.4	4.9	4.4	7.8	6.8	5.1	8.1	8.6	6.5	9.5
Breeding	1.8	2.4	2.0	2.1	2.7	1.7	4.8	4.4	2.4	6.0	2.5	2.3	4.6	3.4	2.3	4.3	4.6	3.0	5.5
Poultry ³	14.5	12.3	12.6	15.4	13.5	13.3	15.7	12.6	12.3	13.0	14.2	14.1	16.5	11.2	10.6	14.3	14.9	14.3	15.7
Hens ±1 yr	9.4	8.6	9.4	8.6	10.1	9.3	14.7	10.2	8.0	11.6	9.0	8.4	15.8	9.3	8.5	12.8	13.2	11.6	14.6
Pullets	5.9	5.3	5.9	6.2	7.6	5.7	18.5	12.0	5.8	16.5	6.8	5.6	18.5	7.5	5.4	17.7	13.2	6.8	18.9
Broilers	16.8	16.1	16.0	18.3	15.6	15.5	17.8	15.9	16.0	15.4	17.7	17.7	17.9	15.7	15.6	17.1	17.7	17.6	18.2
Turkeys ⁸	10.3																		
Ducks ⁸	7.4																		
Sheep ³	8.2				8.3														
Goats ⁵	9				10.4														
Horses ⁸	5.65				7.2														
Mules/ Asses ⁸	7.2																		
Camels ⁸	11.5																		

Note: Brazil (Latin America), with high productivity, was considered to have an excretion rate of 9.3 for layers.

Appendix B – Table 10.19 Default values for Nitrogen excretion rate, according to IPCC (2019)

Values corresponding to the Latin American standard for nitrogen excretion rate, considering laying hens aged over one year.

Category of animal	Region																				
	North America	Western Europe	Eastern Europe	Oceania	Latin America			Africa			Middle East			Asia			India sub-continent				
					Mean	High PS ¹	Low PS ¹	Mean	High PS	Low PS	Mean	High PS	Low PS	Mean	High PS	Low PS	Mean	High PS	Low PS		
Dairy cattle ³	0.60	0.50	0.42	0.72	0.39	0.60	0.28	0.44	0.41	0.45	0.50	0.49	0.51	0.44	0.55	0.41	0.65	0.51	0.70		
Other cattle ³	0.40	0.42	0.47	0.46	0.31	0.36	0.29	0.44	0.42	0.45	0.55	0.51	0.58	0.38	0.36	0.38	0.44	0.63	0.40		
Buffalo ³	NA	0.45	0.35	NA	0.41			0.41			0.39			0.44			0.57				
Swine ⁴	0.39	0.65	0.63	0.54	0.59	0.55	0.67	0.44	0.33	0.49	0.66	0.67	0.56	0.61	0.54	0.67	0.68	0.63	0.71		
Finishing	0.46	0.76	0.77	0.72	0.73	0.69	0.80	0.49	0.39	0.54	0.73	0.75	0.60	0.70	0.63	0.76	0.76	0.74	0.76		
Breeding	0.24	0.38	0.36	0.31	0.35	0.32	0.43	0.29	0.21	0.35	0.40	0.41	0.37	0.37	0.32	0.43	0.43	0.37	0.47		
Poultry ⁴	1.45	0.99	0.96	1.42	1.20	1.13	2.14	1.29	1.16	1.44	1.29	1.27	1.79	1.10	1.00	1.62	1.62	1.48	1.83		
Hens >= 1 yr	1.13	0.87	0.81	1.04	1.17	1.02	2.01	1.20	0.99	1.34	1.11	1.06	1.70	1.00	0.89	1.50	1.65	1.60	1.70		
Pullets	0.77	0.58	0.58	0.76	0.95	0.68	2.50	1.29	0.70	1.72	0.85	0.74	2.03	0.83	0.60	1.91	1.63	0.98	2.20		
Broilers	1.59	1.14	1.12	1.59	1.23	1.21	2.39	1.40	1.34	1.58	1.43	1.42	1.95	1.35	1.31	1.84	1.58	1.47	2.11		
Turkeys ¹²	0.74																				
Ducks ¹²	0.83																				
Sheep ⁴	0.35	0.36	0.36	0.43															0.32		
Goats ⁵	0.46	0.46	0.44	0.42															0.34		
Horses and mules and asses ¹²	0.30	0.26	0.30	0.30															0.46		

Note: Brazil (Latin America), with high productivity, was considered to have an excretion rate of 1.02 for layers.

Appendix C – Default emission factor for direct N₂O emissions in manure management, according to IPCC (2019)

In this study, the Composting type management system in windrows with regular turning for mixing and aeration was considered.

System	Definition	EF ₃ [kg N ₂ O-N (kg Nitrogen excreted) ⁻¹]	
Pit storage ¹³ below animal confinements	Collection and storage of manure usually with little or no added water typically below a slatted floor in an enclosed animal confinement facility.	0.002	
Anaerobic ¹⁴ digester	Anaerobic digesters are designed and operated for waste stabilization by the microbial reduction of complex organic compounds to CH ₄ and CO ₂ , which is captured and flared or used as a fuel.	0.0006	
Burned for fuel or as waste	The dung is excreted on fields. The sun dried dung cakes are burned for fuel.	The emissions associated with the burning of the dung are to be reported under the IPCC category 'Fuel Combustion' if the dung is used as fuel and under the IPCC category 'Waste Incineration' if the dung is burned without energy recovery.	
	Urine N deposited on pasture and paddock	Direct and indirect N ₂ O emissions associated with the urine deposited on agricultural soils and pasture, range, paddock systems are treated in Chapter 11, Section 11.2, N ₂ O emissions from managed soils.	
Cattle and swine deep bedding	As manure accumulates, bedding is continually added to absorb moisture over a production cycle and possibly for as long as 6 to 12 months. This manure management system also is known as a bedded pack manure management system and may be combined with a dry lot or pasture.	No mixing ¹⁵	0.01
		Active mixing ¹⁶	0.07
Composting - In- Vessel ^{3,17}	Composting, typically in an enclosed channel, with forced aeration and continuous mixing.	0.006	
Composting - Static Pile ³ (Forced aeration) ^{4,18}	Composting in piles with forced aeration but no mixing.	0.010	
Composting - Intensive Windrow ^{3,19} (Frequent turning)	Composting in windrows with regular turning for mixing and aeration.	0.005	
Composting- Passive windrow (infrequent turning) ^{4,20}	Composting in windrows with infrequent turning for mixing and aeration.	0.005	
Poultry manure with litter ²¹	Similar to deep bedding systems. Typically used for all poultry breeder flocks and for the production of meat type chickens (broilers) and other fowl.	0.001	
Poultry manure without litter ²¹	May be similar to open pits in enclosed animal confinement facilities or may be designed and operated to dry the manure as it accumulates. The latter is known as a high-rise manure management system and is a form of passive windrow composting when designed and operated properly.	0.001	

Note: In this study EF 3 = 0.005 was considered.

Appendix D – Default emission, volatilization and leaching factors for indirect soil N₂O emissions, according to IPCC (2019)

These values represent the standard emission, volatilization and leaching factors for indirect N₂O emissions into soil.

Emission factor	Aggregated		Disaggregated		
	Default value	Uncertainty range	Disaggregation	Default value	Uncertainty range
EF ₄ [N volatilisation and re-deposition] ¹ , kg N ₂ O–N (kg NH ₃ –N + NO _x –N volatilised) ⁻¹	0.010	0.002 - 0.018	Wet climate	0.014	0.011 – 0.017
			Dry climate	0.005	0.000 – 0.011
EF ₅ [leaching/runoff] ² , kg N ₂ O–N (kg N leaching/runoff) ⁻¹	0.011	0.000 - 0.020	-	-	-
Frac _{GASF} [Volatilisation from synthetic fertiliser] ³ , (kg NH ₃ –N + NO _x –N) (kg N applied) ⁻¹	0.11	0.02 - 0.33	Urea	0.15	0.03 – 0.43
			Ammonium-based	0.08	0.02 – 0.30
			Nitrate-based	0.01	0.00 – 0.02
			Ammonium-nitrate-based	0.05	0.00 – 0.20
Frac _{GASM} [Volatilisation from all organic N fertilisers applied, and dung and urine deposited by grazing animals] ⁴ , (kg NH ₃ –N + NO _x –N) (kg N applied or deposited) ⁻¹	0.21	0.00 - 0.31	-	-	-
Frac _{LEACH-(H)} [N losses by leaching/runoff in wet climates] ⁵ , kg N (kg N additions or deposition by grazing animals) ⁻¹	0.24	0.01 – 0.73	-	-	-

Note: In this study it was considered: EF 4 = 0.01; EF 5 = 0.011; Frac gasf = 0.11; Frac gasm = 0.21; Frac leach = 0.24.

Appendix E – Methane emission factors by animal category, manure management system and climate zone, according to IPCC (2019)

In this study, the “poultry” category was considered, which is the closest to the laying hen animal category. The manure storage system is solid, with a predominant semi-humid tropical climate, with two well-defined seasons, with a dry winter and a very hot and rainy summer.

Livestock species	Productivity Class	Manure Storage System ⁴	Cool				Temperate		Warm			
			Cool Temp. Moist	Cool Temp. Dry	Boreal Moist	Boreal Dry	Warm Temp. Moist	Warm Temp. Dry	Tropical Montane	Tropical Wet	Tropical Moist	Tropical Dry
Poultry	High productivity	Uncovered anaerobic lagoon	156.8	175.1	130.7	128.0	190.7	198.6	198.6	209.0	209.0	209.0
		Liquid/Slurry, and Pit storage below animal confinements > 1 month ⁵	54.9	67.9	36.6	36.6	96.7	107.1	154.2	198.6	190.7	193.4
		Solid storage	5.2				10.5		13.1			
		Dry lot	2.6				3.9		5.2			
		Anaerobic Digestion - Biogas ⁸	5.2				10.5		13.1			
	Burned for fuel	2.6										
	Low productivity	All Systems	2.4									
Sheep	High productivity	Solid storage	2.5				5.1		6.4			
		Dry lot	1.3				1.9		2.5			
	Low productivity	Solid storage	1.7				3.5		4.4			
		Dry lot	0.9				1.3		1.7			
Goats	High productivity	Solid storage	2.4				4.8		6.0			
		Dry lot	1.2				1.8		2.4			
	Low productivity	Solid storage	1.7				3.5		4.4			
		Dry lot	0.9				1.3		1.7			

Note: In this study it was considered: In this study it was considered: EF 7 = 10.5.

Article

Environmental Impacts of the Brazilian Egg Industry: Life Cycle Assessment of the Battery Cage Production System

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† Passed away.

Featured Application: The topic addressed is highly relevant to the Brazilian Egg Production Industry.

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Simple Summary: Promoting sustainability in food production has become essential to meet market demands, mainly due to its tendency to expand throughout the world. Life cycle assessment is a methodology recognized for providing quantitative information on the environmental impacts caused throughout the production cycle in different categories. The objective of this study was to carry out an assessment of the life cycle, from the cradle to the farm gate, following ISO 14040 and 14044 standards, for the battery cage egg production systems and associated products in Brazil. The results showed that interventions focused on feed formulation, manure management, and the welfare of laying hens play a fundamental role in promoting sustainability in battery cage egg production systems.

Abstract: Brazil stands as one of the world's leading producers of animal protein, ranking sixth in global egg production. However, estimated growth in production demand, along with environmental impacts, represents a potential threat to the sustainability of the food system. Methods for assessing and quantifying the environmental impacts generated by Brazilian egg production remain scarce, lacking current reports on comparative effects or guiding standards. The objective of this study was to conduct a life cycle assessment from cradle to farm gate, adhering to ISO 14040 and 14044 standards, for the battery cage egg production systems and associated products in Brazil, with the aim of supporting and promoting sustainability improvements in the Brazilian egg industry. The entire life cycle modeling and process sustainability analysis were executed using the openLCA software, integrated with the Ecoinvent database. Emissions related to egg production yielded results of 65.06 kg SO₂ eq., 27.74 kg N eq., 3086.71 kg CO₂ eq., 75,152.66 CTUe, 2.75 × 10⁻⁵ CFC-11 eq., and 10,044.68 kg MJ eq. per ton of eggs produced. These findings can serve as

comparative benchmarks for future studies and for analyzing data across different egg production systems in Brazil.

Keywords: agricultural sector; egg production; intensive system; sustainability; LCA; LCI; LCIA

1. Introduction

Brazil is recognized as a significant player in the global animal protein market, holding prominent positions in various categories. In 2022, the country was the second-largest producer of both beef and chicken, leading the way in exporting these two products. Moreover, Brazil stands as the fourth-largest pork producer and holds the fourth position in the global pork export market [1,2]. Additionally, Brazil has claimed the sixth spot in egg production, with a staggering output exceeding 52.06 billion units [3]. According to the ABPA (Brazilian Animal Protein Association) [1], 99.6% of Brazilian egg production is destined for the national market, and only 0.44% is destined for the international market, with expectations of significant growth in egg exports in the coming years. Despite the share of the export market, where 57% consists of fresh eggs and 43% of processed ones, Brazilian eggs have found their way into families' households in 83 consumer countries around the world. These nations are distributed across different regions, with the Middle East accounting for the largest share at 64.41% of the import market, followed by the Americas (16.42%), Asia (14.49%), Africa (1.42%), Oceania (1.37%), the European Union (1.16%), and Europe Extra-EU (0.46%) [1,3].

The anticipated increase in demand for animal-derived products, along with the corresponding environmental consequences, represents a potential threat to the sustainability of the entire food system. This encompasses production, processing, and distribution, collectively responsible for generating 21% to 37% of global greenhouse gas (GHG) emissions [4]. As reported by the Food and Agriculture Organization (FAO) [5] and the Intergovernmental Panel on Climate Change (IPCC) [6], global emissions from these systems witnessed an approximate 16% increase between 1990 and 2019, with expectations of continued growth. Therefore, it becomes imperative to identify and disseminate best practices in sustainability management with the aim of achieving reductions in production-related impacts.

Sustainability in livestock production is related to various critical aspects such as food security, public health, worker safety, biodiversity loss, economic accessibility, and animal welfare [7]. As a result, the challenge within the animal production system, especially in activities related to the egg industry, lies in a delicate balance among all these environmental factors while simultaneously meeting the existing production demands [7,8].

The prevailing egg production system in Brazil is the battery cage system, implemented in open or semi-open barns, comprising around 95% of the national egg production. Within this production system, two main types of installations are prominent, distinguished by the arrangement of the cages: the pyramid or Californian model and the vertical model [9]. On the other hand, extensive or alternative systems, including cage-free, free-range, organic, and "colonial" (traditional), collectively represent an estimated 5% of Brazilian production. However, it is noteworthy that statistical production authorities do not effectively quantify these alternative systems [9,10]. These systems represent distinct characteristics inherent to housing design and management, including feeding

(particularly in the case of organic systems) and the overall cost of egg production [11].

In Brazil, there is a shortage of methods to assess and quantify the environmental impacts associated with egg production. Currently, there are no existing records for comparative effects or guidelines for enhancing production practices. As a result, the adoption of new production systems is being implemented at a slow pace due to the potential impact on the product's pricing and its accessibility to consumers [12].

Life Cycle Assessment (LCA) is regarded as a leading tool for evaluating the environmental performance of a production system [13]. LCA is an internationally standardized method, and its application is governed by ISO14040–14044 standards [14,15]. LCA serves as a method to assess the potential environmental and human health impacts of products and services throughout their life cycle, starting from raw material extraction and covering all stages of production, transportation, manufacturing, use, and end-of-life treatment [16]. It is important to emphasize that LCA applications enable the estimation of potential environmental impacts over the life cycle of a system, quantifying, within current scientific and data limitations, the likely emissions produced and resources consumed. Furthermore, LCA identifies “hotspots” within the supply chain that may be prioritized for sustainability improvement efforts [17]. Therefore, the environmental impacts calculated through LCA should not be interpreted as absolute values but rather as relative within the scope of the study [18].

As a calculation tool, the open-source LCA software OpenLCA, version 2.0 [19], was used in conjunction with the Ecoinvent database, version 3.9.1. These databases incorporate a set of flows, including product flows, elementary flows (extracted from the environment without prior human transformation), and waste flows [20]. Processes are then established based on these flows, which are listed and quantified as inputs/outputs (through inventory data), consequently allowing the creation of a comprehensive product system. By defining a product system, it is possible to calculate the impacts generated using the desired impact assessment method [21].

LCA has been extensively applied to various egg production systems globally, including countries such as the Czech Republic [22], Canada [23–26], Mexico [27], the USA [28], Spain [29], the UK [30,31], Australia [32], the Netherlands [33], and Sweden [34], among others. Across these studies, there is a consistent identification of feed production and manure management practices as the principal contributors to the environmental impacts within the egg production chain. However, these findings collectively offer valuable insights and opportunities for interventions aimed at enhancing the sustainability of egg production.

In order to support and promote sustainability improvements in the Brazilian egg industry, this study aims to conduct an LCA from cradle to farm gate, following ISO 14044 guidelines [15], for the battery cage-based egg production system and related products. Specifically, this study seeks to quantify the use of resources and emissions attributable to the evaluated production system, including specific production inputs. It aims to identify mitigation potential and specific interventions to enhance resource use efficiency and reduce emissions from Brazilian egg production. In the future, the baseline model developed in this study could be utilized to support additional analyses and comparisons investigating strategies for environmental impact mitigation. It could also contribute to production improvement plans, such as increasing efficiency and resource use, implementing new technologies, incorporating renewable energy, optimizing natural resources, and valorizing manure, among other strategies [35–38].

2. Material and Methods

2.1. Scope of the Study

2.1.1. Brazilian Egg Production Chain

This study utilized a database sourced from a farm located in the Brazilian Midwest, a region characterized by a predominantly semi-humid tropical climate, describing two well-defined seasons—dry winter and hot, rainy summer [39]. The farm is organized into five sectors: a feed mill, pullet barns, laying barns, a sorting and dispatch area, and a composting area designated for manure management.

In the upstream segment of the egg production chain, inputs are primarily sourced from the production of crops such as corn and soybeans, along with the production of one-day-old chicks [40]. These inputs are directed into the farm and specifically allocated to the feed mill and pullet barns, where they play an important role in the production of pullets.

Within the farm, a feed mill is dedicated to the production of mashed feed, and the entire manufacturing process is automated—from the measurement of inputs to the dispatch of the feed. The types of feeds produced vary in accordance with the production phases of laying hens and their specific nutritional requirements at each stage [41]. The eleven pullet barns, along with the forty-eight laying barns, are structured in the conventional system of vertically arranged cage pullet. From 1 to 14 days of age, chicks are accommodated in cages with dimensions of 0.74×0.58 m, hosting an average of 67 chicks per cage (64 cm^2 per chick). Commencing on the 15th day of age, a distribution process is initiated, transferring the chicks to pullet production cages with dimensions of 0.70×0.80 m. These cages house an average of 17 pullets each (330 cm^2 per pullet), and they remain in the pullet barns until the 17th week of age. After this period, there is a transfer process from the pullet barns to the laying barns, where the laying hens will stay for 88 weeks. These laying barns are equipped with cages of the same dimensions but with an average of 13 laying hens per cage (430 cm^2 per laying hen). At the conclusion of the production cycle, after 88 weeks, spent hens are subsequently evaluated and sold to processing plants.

The eggs from the laying facilities are transferred to the grading sector through an external conveyor system. In this sector, the eggs undergo anomaly detection and are categorized based on size and quality as type A, B, or C eggs. Type A eggs, which are in perfect condition for sale, are packaged and sent to the dispatch sector. Eggs with small cracks, categorized as type B, are packaged and sent to another unit for the production of liquid eggs. The egg-breaking sector is responsible for producing whole liquid eggs, which are stored and frozen in 18-L buckets, known as industry eggs—type C. All eggs go through a series of hygiene processes before their classification, including washing, enhanced with mineral oil, and are later directed to pack and dispatch or for egg-breaking facilities.

The removal of manure from the pullet and laying barns occurs daily through automated conveyors, depositing the collected manure into external containers. These containers are then transported by truck and unloaded in the composting area, along with all the organic manure generated in the unit. Mortalities experience a dehydration process in furnaces and are also deposited in the composting area. It is worth noting that the twelve composting barns store 99% of bird manure and only 1% of other residues. Consequently, the manure undergoes a biotechnological process of organic matter decomposition under controlled aerobic conditions, and to enhance the process, low-moisture materials such as wood chips are introduced, resulting in the co-product organic compost. This compost is then sold to local producers in the region. Figure 1 illustrates the Brazilian egg production chain in a battery cage system.

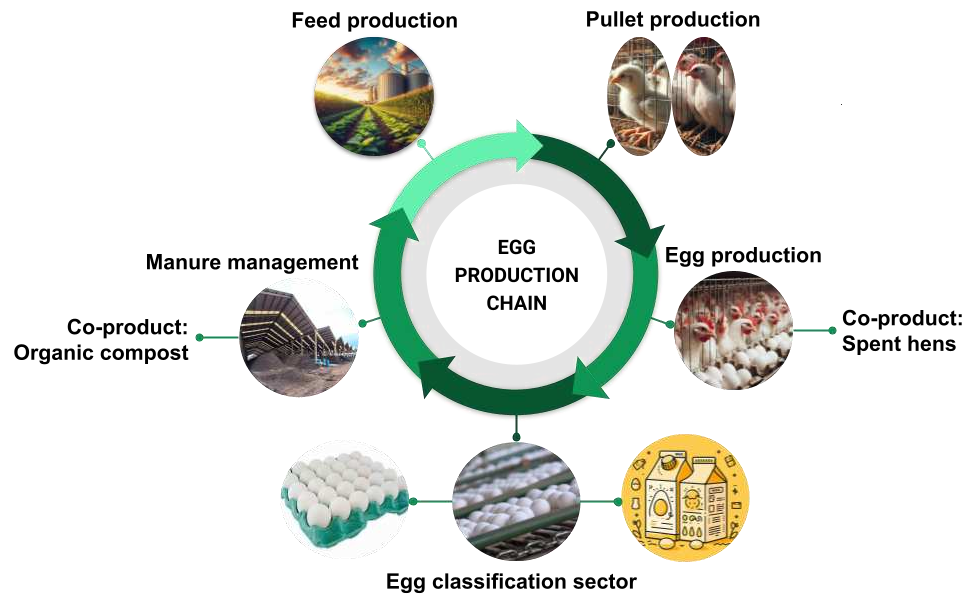


Figure 1. Egg production chain of Brazilian eggs in a battery cage production system. Source: The authors.

2.1.2. System Boundaries

The system boundaries for this study comprise all pertinent flows of materials, energy, and emissions in all considered processes, in accordance with ISO 14044 guidelines [15], ranging from cradle to farm gate. This includes all processes related to feed production (inputs, energy, and water); the production of pullets and layers of hens (chicks, feed, energy, water, and manure management); as well as all processes associated with egg grading and processing (eggs, energy, packaging, and water). The internal transportation of material flows between the stages of the supply chain is also considered. Nevertheless, it is important to note that the transportation of eggs and derivatives to retail is not considered in this study, as it occurs beyond the farm gate and falls outside the defined system boundaries.

The processing of chickens for human consumption is also excluded as it is outside the system's boundaries. Regarding the production of organic compost, despite occurring within the farm, it is treated as a co-product derived from the reuse of manure, aligning with the criteria outlined by ISO 14044 [15], which incorporates co-product allocation criteria based on products or residues classified as reusable. In this way, the valorization of spent hens, which are no longer discarded in the environment and are now used for consumption, and the production of organic compost that directs and reuses manure as a source of organic fertilizers are both regarded as allocation factors in evaluating these two co-products. Figure 2 illustrates the system boundaries for an LCA of Brazilian egg production in a battery cage system.

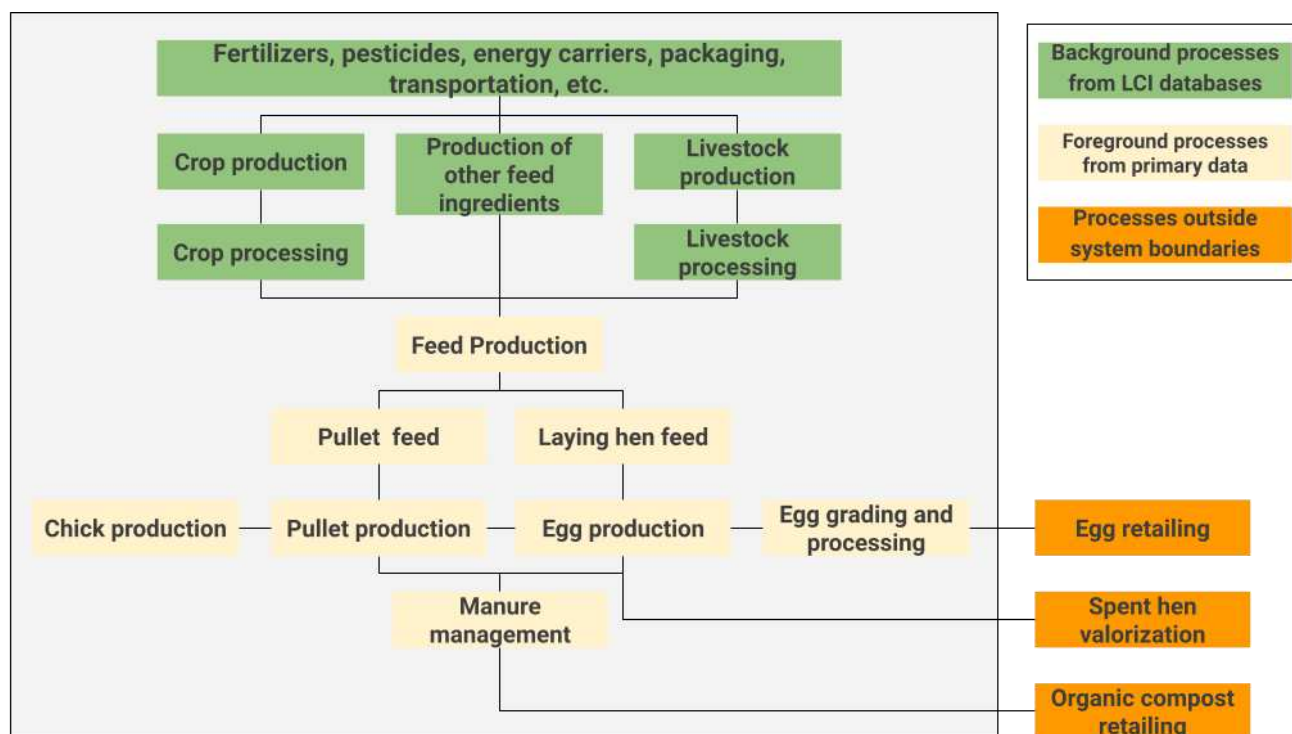


Figure 2. Limits of the LCA system from cradle to gate of egg production Brazilian eggs in the battery cage production system. Source: Turner et al. [23]; adapted by the authors.

2.1.3. Functional Unit

Different functional units (FUs) were employed to describe the results at each stage of the production chain. In feed production, the functional unit was one ton of feed produced; in pullet production, it was 1000 pullets produced; in egg production (layers), the functional unit was one ton of eggs produced; in grading, it was one ton of graded eggs; and in liquid egg production, the functional unit was one ton of liquid eggs produced. All data are applicable to the base year of 2021.

2.1.4. Co-Product Allocation

ISO 14044 [15] defines a co-product as one of two or more products originating from the same elementary process. Many agri-food production systems involve multifunctional processes, presenting a common challenge of allocating impacts among co-products [42]. In this study, the egg is considered the main product, with production categorized into Type A eggs (90.31% of production), Type B eggs (9.44%), and Type C eggs, which are marketed in refrigerated buckets (0.25%). Market estimates indicate significant variations in egg prices throughout the year 2021. According to CEPEA [43], the mean price of white eggs remained at approximately BRL127.21 per box with 360 units (equivalent to approximately 21.6 kg of eggs) in the central-west region of Brazil.

The co-products considered in this study are the valorization of spent hens and the production of organic compost derived from manure. According to information from the farm, spent hens are sent to processing plants with an average weight of 1.8 kg (ranging from 1.6 to 2 kg) and are commercialized at a rate of BRL 1.5 per kilogram of hen. Once produced, the organic compost is distributed to local producers without any stock of the finished compost. This compost has a high demand, with a market price of BRL 600 per ton. However, it is emphasized that eggs are the primary product of the system and the most significant in terms of nutrition, mass, and economic value [44].

2.1.5. Cutting and Exclusion Criteria

In this study, the incubation of chicks was not considered, as the acquisition of chicks is outsourced by the farm and is outside the defined system limits. Previous studies proposed by Pelletier et al. [28], Pelletier [24,25], and Turner et al. [23] suggest that, although necessary for a comprehensive LCA, breeding batches and incubation facilities make relatively trivial contributions to the overall life cycle impacts in the egg industry.

Modeling for medication use, including antibiotics, cleaning products, and enteric fermentation for hens, as well as the maintenance of infrastructure, such as machinery and farm buildings, was excluded from the evaluation.

In this assessment, a single average value for egg mass (60 g) was considered, following the farm's guidelines, rather than accounting for a distribution of sizes of produced eggs, as suggested by Ibarburu et al. [45].

In the present study, a single egg-producing farm was considered within the battery cage production system. However, obtaining foreground data remains a challenge in the country. It is remarkable that the evaluated farm has a high production potential, pioneeringly representing the domestic market by producing over 1.2 billion units of eggs in 2021 and experiencing growing demand in the international market.

2.2. Life Cycle Inventory—LCI

2.2.1. Data Sources and Assumptions

The foreground system data are those directly collected from producers within the supply chain under study, incorporating inputs and outputs of products, as well as emissions related to the various stages of the production chain [24]. The foreground system data for this study were collected jointly with the farm through answers to questionnaires and meetings with the responsible sectors involved in feed production, pullet and laying hen production, egg grading, liquid egg production, and manure management, ensuring that the data source remained confidential throughout the process.

Background system data are obtained through information derived from an LCI database, with support for various types of sustainability assessments that constitute one of the most critical steps in the LCA process [46]. In this study, production and supply models for food inputs, water, energy, packaging, and transportation means were utilized, sourced from the EcoInvent database [47,48], and modified whenever possible to better align with Brazilian conditions.

Modeling N, P and CH₄ Emissions from Manure

The values related to volatile solids excreted were considered in accordance with the IPCC [49,50], along with the annual quantity of excreta produced by the farm. To calculate nitrogen (N) excretion, a mass balance was performed based on feed consumption, jointly with the assessment proposed by ASAE [51] and França [52]. Phosphorus (P) excretion was also determined through a mass balance based on feed consumption. For P loss estimates, a value of 3.48% was assumed, representing the expected average losses in Brazil, in accordance with the average rates found by Rittmann et al., Piovesan, and Peles [53–55].

The percentages of N and P in the feed for pullets and laying hens were calculated based on the nutritional levels specified in the composition of both formulations, as provided by the farm, with the percentage of 18.5% crude protein (CP) and 0.6% phosphorus (P) for the pullet feed, and 16.7% CP and 0.52% P for the laying hen feed.

The estimates of nitrogen emissions applied to the soil were calculated by subtracting the N emitted during manure management from the nitrogen

excreted. The values for nitrous oxide (N₂O), nitrate (NO₃), nitric oxide (NO_x), ammonia (NH₃), and methane (CH₄) were computed using Tier 1 and 2 equations from the IPCC guidelines [49,50]. As a result, the estimated values are 4.85 kg N₂O, 68.45 kg NO₃, 48.92 kg NH₃, 12.00 kg NO_x, 27.01 kg CH₄, and 3.56 kg P₂O₅ per 1000 units of caged pullets produced; and 1.99 kg N₂O, 31.91 kg NO₃, 22.42 kg NH₃, 5.50 kg NO_x, 3.18 kg CH₄, and 1.21 kg P₂O₅ per ton of eggs produced. Tables S1 and S2 in Supplementary S1—Supplementary Information provide a comprehensive description of the considered values.

Modeling of Food Inputs

The feed compositions considered comprise a total of ten formulations, with five feeds designated for the pullet phase, named Pre-Starter, Starter, Grower, Maturity, and Pre-Laying; and five feeds designated for the laying phase, named Start, Peak, Laying 1, Laying 2, and Laying 3. The Pre-Starter feed, when used, starts on the first day of the chick's life and continues until the second week, concluding at 14 days. In most cases, the Starter feed is adopted from the first day until the sixth week, concluding at 42 days. The Grower feed is used from the 7th to the 10th week, concluding at 70 days. The Maturity feed is used from the 11th to the 15th week, ending at 105 days, and can be used up to the production phase, reaching 17 weeks. The Pre-Laying feed, when used, starts in the 16th week until the start of production in the 17th week, concluding at 119 days. For the feeds destined for the laying phase, the Start feed begins in the 18th week and continues until the 30th week, concluding at 210 days. The Peak feed, from the 31st week to the 50th week, concluded at 350 days. Laying 1 feeds from the 51st week to the 70th week, concluding at 490 days. The Laying 2 feeds from the 71st week to the 90th week, concluding at 630 days. Finally, the Laying 3 feeds from the 91st week until the disposal of the laying hen, which can vary from 770 days to 875 days when the molting process occurs. These feed compositions are estimated/used by the farm as needed. The compositions of the feeds for the pullet and laying houses can be found in Tables S3 and S4 in Supplementary S2—Supplementary Information.

After analyzing the quantity of all compositions, a unified formulation was considered for both pullet and laying phases, as considered in studies proposed by Pelletier et al. [28], Pelletier [24,25], and Turner et al. [23]. In all feed compositions, corn and soy (derivatives) emerge as the predominant food ingredients. For this assessment, ingredients constituting less than 1% of the composition were not considered. The inventory models for feed production were derived from the EcoInvent database, in collaboration with the Sustell platform, which integrates major LCA agro-food databases such as Agri-footprint and GFLI [56–58].

2.2.2. Assessment of Data Quality and Uncertainty

ISO 14044 [15] requires an assessment of data quality to ensure that low-quality data do not adversely impact the results. These assessments can contribute to improvements in data quality but also help to identify key variables for sensitivity analyses [24].

Data quality was evaluated according to each flow across all foreground processes using the standard EcoInvent pedigree matrix, as outlined by Ciroth et al. [59], described in Table S5 in Supplementary S3—Supplementary Information. The assessment of data quality for flows in all processes was evaluated based on reliability, integrity, and temporal, geographical, and technological correlation within the modeling context. A scoring scale from 1 to 5 was employed in this system, with 1 indicating the highest quality data and 5 indicating the lowest

quality data. The specific assignments for each process are presented in Table S6 in Supplementary S4—Supplementary Information [21].

Pelletier [24,25] categorizes uncertainties in LCA studies into three types: inventory data uncertainty, characterization model uncertainty, and LCI model uncertainty. Bamber et al. [60] concluded in their studies that less than 20% of LCA studies published between 2014 and 2018 reported any form of uncertainty analysis. While inventory data uncertainty is most frequently reported (82% of the studies), other sources of uncertainty are considered equally important. Monte Carlo analysis emerged as the most popular method, utilized by 61% of publications to propagate uncertainty results, regardless of the type of LCA. Using the OpenLCA software, both data quality and uncertainty values were calculated from matrices and Monte Carlo simulations [19,21].

2.3. Life Cycle Impact Assessment—LCIA

2.3.1. Impact Assessment Method and Indicators

According to the ISO 14044 guidelines [15], the LCIA phase should consider a comprehensive set of impact categories related to the product system under study. To determine a consensus set of impact categories most relevant to egg production systems, a review of LCA studies on egg production was conducted, as outlined by Maciel et al. [17].

Among the assessed impact categories, there was significant diversity in the impact categories considered in LCA studies for eggs across different countries. The analysis of 20 sources covering 10 different countries, including the Czech Republic, Canada, the United Kingdom, Serbia, the USA, Italy, Sweden, Mexico, the Netherlands, and Spain, identified a total of 25 different impact categories. Emissions related to global warming potential (CO₂ eq.) were unanimously considered in all studies, followed by acidification (SO₂ eq.), eutrophication (N eq.), ecotoxicity (CTUe), ozone depletion (CFC eq.), and cumulative energy demand fossil (MJ eq.), ranging from 65% to 55% of the studies. Other related impacts were not considered, as they remained below 50% of the analyzed studies and did not align with the reality of egg production considered in Brazil. Therefore, the impact categories to be evaluated include acidification, eutrophication, global warming potential (GWP), ecotoxicity, ozone depletion, and cumulative fossil energy demand (CED), as shown in Table 1.

Table 1. Selected impact categories for the assessment of environmental impacts in egg production and their characterization factor units.

Impact Categories	Characterization Factor Unit
Acidification	kg SO ₂ eq.
Eutrophication	kg N eq.
Global warming potential (GWP)	kg CO ₂ eq.
Ecotoxicity	CTUe (unidades tóxicas comparativas)
Ozone depletion	kg CFC-11 eq.
Cumulative Energy Demand (CED) fossil	MJ eq.

2.3.2. Comparisons with Other Studies

LCIA Egg Production

International studies report the environmental performance of battery cage egg production; however, direct comparisons between studies are uncertain due to frequent differences in the considered modeling. Nevertheless, it is interesting to consider and compare the impacts reported by various studies, including Guillaume et al. [22], Turner et al. [38], Estrada-González et al. [27], Abín et al. [29], Pelletier [24,25], Pelletier et al. [28], Leinonen et al. [30,31], Wiedemann and

McGahan [32], Mollenhorst et al. [33], Cederberg et al. [34], and Vergé et al. [26], to the findings of the current study.

Although there are currently no publications on LCA for Brazilian egg production, a series of LCAs have been conducted for agricultural industries in response to the growing demand for information on food products and supply chains [32]. The authors Dick et al. [61], Cardoso et al. [62], Willers et al. [63], Dick et al. [64], Leis et al. [65], Carvalho et al. [66], Barros et al. [67], Maciel et al. [68], Silva et al. [69], Lima et al. [70], Alves et al. [71], Cherubini et al. [72], and Alvarenga et al. [73] describe Brazilian LCA, considering key agro-industrial products such as beef cattle, dairy cattle, broiler chickens, pork, and broiler feed, across their various production systems.

More specific studies get into the assessment of product quality in special confinement systems, reflecting the trend toward qualitative consumption of products, as indicated by Morais et al. [74]. In their study, they concluded values of 5.03, 4.77, and 8.89 kg of CO₂ eq./kg of live weight gain in confinement for premium, super-premium Angus, and super-premium Wagyu meats, respectively.

3. Results

3.1. Life Cycle Inventory Results

The LCI data are presented in Tables 2–7, corresponding to the functional unit of each production.

Table 2. Percentage of feed composition for pullets and laying hens per ton of feed produced.

Ingredients	% Feed Pullets	% Feed Laying Hens
Maize	65.28	62.19
DDGs	–	8.00
Limestone	1.83	10.11
Methionine	0.29	0.19
Meat and Bone Meal	4.01	2.06
Salt	0.35	0.20
Soybean meal	20.31	14.87
Soybean hull	7.25	1.30
Vegetable oil	–	0.11
Vitamins and minerals	0.34	0.65
Soy oil	–	0.32
Others	0.34	–

Table 3. LCI data for producing 1000 units of broiler chickens in battery cage systems.

	2021 Average Pullets Production
Inputs	
Chicks (units) ^a	1025
Mass/Chicks (g) ^a	35
Transportation (t*km) ^a	37.10
Feed (tons) ^a	5.48
Transportation (t*km) ^a	7.31
Water (m ³) ^{ab}	14.38
Electricity (kWh) ^a	227.32
Diesel (L) ^{ab}	80.88

Table 3. *Cont.*

2021 Average Pullets Production	
Outputs	
Pullets (unit)	1000
Mass (tons) ^a	1.21
Manure (tons) ^{ab}	4.27
Transportation (t*km) ^a	5.71
N excreted (kg) ^b	162.06
P excreted (kg) ^b	33.29
Mortality rate (%) ^a	2.35
Transportation (t*km) ^a	0.02

^a Based on primary research data; ^b Data estimated, modeled, or taken from the literature; ^{ab} Total primary data and estimate (by sector).

Table 4. LCI data for producing one ton of eggs in battery cage production systems.

2021 Average Egg Production	
Inputs	
Pullets (unit) ^a	36.27
Distance (t*km) ^a	11.54
Feed (tons) ^a	2.16
Distance (t*km) ^a	2.89
Water (m ³) ^{ab}	3.07
Electricity (kWh) ^a	102.51
Diesel (L) ^{ab}	7.63
Outputs	
Eggs (tons)	1
Spent hens (kg) ^a	51.50
Mass/spent hens (kg/hen) ^a	1.80
Distance (t*km) ^a	77.25
Manure (tons) ^{ab}	2.06
Distance (t*km) ^a	2.75
N excreted (kg) ^b	57.80
P excreted (kg) ^b	11.36
Mortality rate (%) ^a	13.04%
Distance (t*km) ^a	1.34

^a Based on primary research data; ^b Data estimated, modeled, or taken from the literature; ^{ab} Total primary data and estimate (by sector).

Table 5. LCI data for producing one ton of graded eggs.

Classified Eggs in 2021	
Inputs	
Eggs (kg) ^a	1002.56
Water (m ³) ^{ab}	4.18
Electricity (kWh) ^a	28.82
Packaging (kg)	
Cardboard (kg) ^a	48.36
Plastic film and acrylic (kg) ^a	34.88
Outputs	
Eggs (Type A) (kg) ^a	900.76

Table 5. *Cont.*

	Classified Eggs in 2021
Eggs (Type B) (kg) ^a	94.19
Eggs (Type C) (kg) ^a	2.50
Discarded eggs (kg) ^a	2.56

^a Based on primary research data; ^{ab} Total primary data and estimate (by sector).

Table 6. LCI data for producing one ton of processed liquid egg.

	Production of Liquid Eggs in 2021
Inputs	
Eggs (kg) ^a	1299.13
Transportation (t*km) ^a	1295.23
Water (m ³) ^a	9.08
Electricity (kWh) ^a	195.71
GLP gas (m ³) ^a	9.62
Packaging (kg)	1.89
Cardboard (kg) ^a	1.02
Plastic Film and Acrylic (kg) ^a	0.87
Outputs	
Whole Liquid Eggs (kg) ^a	1000
Eggshells (kg) ^a	138.84
Discarded Eggs (kg) ^a	52.63

^a Based on primary research data.

Table 7. LCI data for producing one ton of organic compost.

	Production of Organic Compost in 2021
Inputs	
Manure Produced	
Poultry Manure (kg) ^{ab}	2360.94
Carcasses and Other Residues (kg) ^{ab}	33.09
Transportation (t*km) ^a	28.33
Water (m ³) ^{ab}	0.08
Diesel (L) ^{ab}	20.90
Shredded Eucalyptus—Wood Chips(kg) ^a	2.78
Outputs	
Organic Compost (kg) ^a	1000

^a Based on primary research data; ^{ab} Total primary data and estimate (by sector).

The data represent a total of 171,703 tons of feed in 2021.

The data represent the production of 2,636,550 pullets in 2021.

The data represent a total egg production of 72,698.23 metric tons in the year 2021.

The data represent the total production of 65,483.60 metric tons of Grade A eggs, which are packaged and sold; 6847.14 metric tons of Grade B eggs, intended for liquid egg production; and 181.63 metric tons of Grade C eggs, which are refrigerated and sold in 18-L buckets. All production values refer to the year 2021.

The data represent the production of 1953.75 metric tons of liquid egg in the year 2021.

The collected data represent the production of 68,156 metric tons of organic compost in the year 2021.

3.2. Allocation Results for Co-Products

Table 8 presents the allocation of co-products, organic compost, and spent hens based on the production quantity in mass (metric tons) and their respective economic value.

Table 8. Co-product allocation and allocation percentage based on mass and economic value.

Product	Mass Production (ton.)	Economic Production (BRL)	Percentage Mass Production (%)	Percentage Economic Production (%)
Egg	72,698.23	742,026,471.7	50	94
Organic compost	68,156	40,893,600	47	5
Spent hens	3744	5,616,000	3	1

The mass production percentages of eggs and organic compost are considered similar when compared (within a 3% variation) but present relevant economic values. Therefore, the economic allocation method is considered more suitable, resulting in an allocation factor of 94% for egg production, 5% for organic compost production, and 1% for the valuation of spent hens.

3.3. Life Cycle Impact Assessment Results

All the results of the LCIA are presented in detail in Tables 9–11, using reference units for each impact category in accordance with the egg production chain.

Table 9. LCIA results per ton of feed produced for the pullet phase.

Impact Category	Pre-Starter Feed	Starter Feed	Grower Feed	Maturity Feed	Pre-Laying Feed
Acidifying emissions (kg SO ₂ eq)	4.48	4.51	4.52	4.49	4.37
Eutrophying emissions (kg N eq)	6.11	6.02	6.04	6.17	5.75
GHG emissions (kg CO ₂ eq)	1285.58	1250.66	1257.31	1303.21	1185.97
Ecotoxicity (CTUe)	42,900.81	41,391.65	41,645.30	43,595.72	39,042.66
Ozone depletion (kg CFC-11 eq)	1.31 × 10 ⁻⁵	1.29 × 10 ⁻⁵	1.29 × 10 ⁻⁵	1.32 × 10 ⁻⁵	1.24 × 10 ⁻⁵
CED fossil (MJ eq)	4332.61	4354.86	4364.24	4348.38	4214.02

Table 10. LCIA results per ton of feed produced for the laying phase.

Impact Category	Starter Feed	Peak Feed	Laying Feed 1	Laying Feed 2	Laying Feed 3
Acidifying emissions (kg SO ₂ eq)	3.93	4.01	4.03	4.04	4.01
Eutrophying emissions (kg N eq)	4.73	4.68	4.71	4.64	4.66
GHG emissions (kg CO ₂ eq)	922.55	895.66	900.45	874.64	886.68
Ecotoxicity (CTUe)	29,169.63	27,897.89	28,045.00	26,964.00	27,534.83
Ozone depletion (kg CFC-11 eq)	1.04 × 10 ⁻⁵	1.04 × 10 ⁻⁵	1.04 × 10 ⁻⁵	1.03 × 10 ⁻⁵	1.03 × 10 ⁻⁵
CED fossil (MJ eq)	3771.96	3833.92	3854.63	3857.02	3828.50

Table 11. LCIA results per ton of feed for pullets and laying hens, per 1000 units of pullets produced, per ton of eggs produced, per ton of graded eggs, and per ton of liquid eggs produced.

Impact Category	Feed Production (Pullets)	Feed Production (Laying Hens)	Pullets Production	Egg Production	Egg Grading	Liquid Egg Production
Acidifying emissions (kg SO ₂ eq)	4.48	4.00	129.46	65.06	65.78	85.30
Eutrophying emissions (kg N eq)	6.02	4.68	64.29	27.74	28.26	36.33
GHG emissions (kg CO ₂ eq)	1256.54	896.00	8365.25	3086.71	3232.93	4355.12
Ecotoxicity (CTUe)	41,714.92	27,922.16	228,568.90	75,152.66	76,676.23	100,286.33
Ozone depletion (kg CFC-11 eq)	1.29 × 10 ⁻⁵	1.04 × 10 ⁻⁵	7.17 × 10 ⁻⁵	2.75 × 10 ⁻⁵	3.04 × 10 ⁻⁵	4.33 × 10 ⁻⁵
CED fossil (kg MJ eq)	4322.82	3829.20	24,117.43	10,044.68	13,541.11	18,436.53

The higher impacts in acidifying emissions and fossil CED observed in the Grower Feed are contrasted by the Maturity Feed, which displays higher impacts in eutrophication, greenhouse gas emissions, ozone depletion, and ecotoxicity. This disparity between the two feeds is linked to the increased percentage of corn-based ingredients (1.4%) in the Grower Feed and soy derivatives (1.8%) in the composition of the Mature Feed.

The Starter Feed exhibits higher impacts related to eutrophication, greenhouse gas emissions, ozone depletion, and ecotoxicity. On the other hand, Laying Feed 2 shows higher impacts related to acidifying emissions and fossil CED. This variation between the Starter Feed and Laying Feed 2 is attributed to the increase in the percentage of soy-derived ingredients (2.2%) and meat and bone meal (1.7%) in the composition of the Starter Feed and corn (3.1%) in the composition of Laying Feed 2.

3.3.1. LCIA Results—Feed Production

When analyzing the LCIA results of one ton of feed produced for pullets, according to impact categories, in acidifying emissions, corn accounts for 82.4% and soy for 17.3%; in eutrophying emissions, corn represents 51.5% and soy for 48.4%; in GHG emissions, corn accounts for 33.7% and soy for 66.1%; in ecotoxicity, corn represents 22.2% and soy for 77.8%; in ozone depletion, corn corresponds to 58% and soy to 41.7%; in fossil CED, corn corresponds to 79% and soy to 20.4% of the generated impacts. Other inputs such as bone meal, limestone, natural resources, and energy account for less than 1% of the impact generated in the production of one ton of feed for pullets.

When analyzing the LCIA results of one ton of feed produced for laying hens, in acidifying emissions, corn accounts for 87.8% and soy for 11.4%; in eutrophying emissions, corn represents 63.11% and soy for 36.5%; in GHG emissions, corn accounts for 45.05% and soy for 54.4%; in ecotoxicity, corn represents 31.6% and soy 68.2%; in ozone depletion, corn corresponds to 68.7% and soy to 30.4%; in fossil CED, corn corresponds to 85% and soy represents 13.5% of the generated impacts. Other inputs such as DDG, bone meal, limestone, natural resources, and energy account for less than 1% of the impact generated in the production of one ton of feed for laying hens.

However, for a better understanding and analysis of the impacts generated by feed production, Figure 3 illustrates the relative percentages of the impacts generated by the feeds.

It is evident that the production of feed for laying hens shows a reduction in generated impacts, ranging from 11% to 33% when compared to feed for pullets.

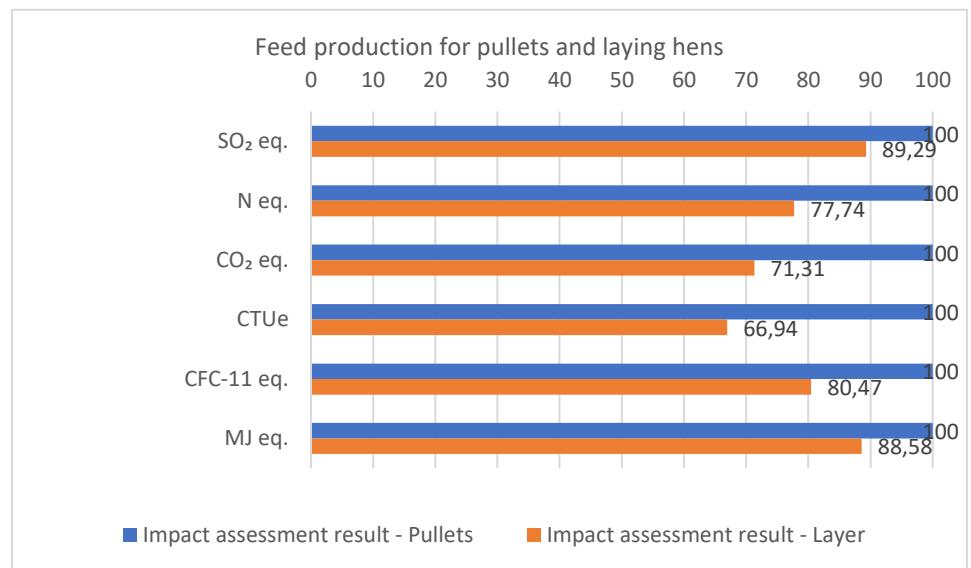


Figure 3. Relative percentage of environmental impacts per ton of feed produced for pullets and laying hens.

3.3.2. LCIA Results—Pullets Production

When analyzing the LCIA results for the production of 1000 units of pullets, it is observed that manure management contributed to impact categories such as acidification, eutrophication, and greenhouse gas emissions, with relatively minor contributions to ecotoxicity, ozone depletion, and fossil CED. However, feed inputs emerge as the primary drivers for ecotoxicity, ozone depletion impacts, and fossil CED.

Considering the generated impacts of acidifying emissions, waste management accounts for 81%, while feed production contributes 18.9%. For eutrophying emissions, feed production represents 51.2%, and manure management contributes 48.7%. In greenhouse gas emissions, feed production corresponds to 82.2% and manure management to 17.3%. In terms of ecotoxicity, feed production constitutes 99.9%, with electricity contributing less than 1%. Ozone depletion is primarily driven by feed production at 98.5%, with electricity contributing 1.3%. Fossil CED is dominated by feed production at 98.1%, while electricity accounts for 1.5% of the generated impacts. Other inputs such as transportation, diesel, and water contribute less than 1% to the impact generated in the production of 1000 units of pullets. Figure 4 illustrates the percentage of impacts generated by the production of 1000 units of pullets.

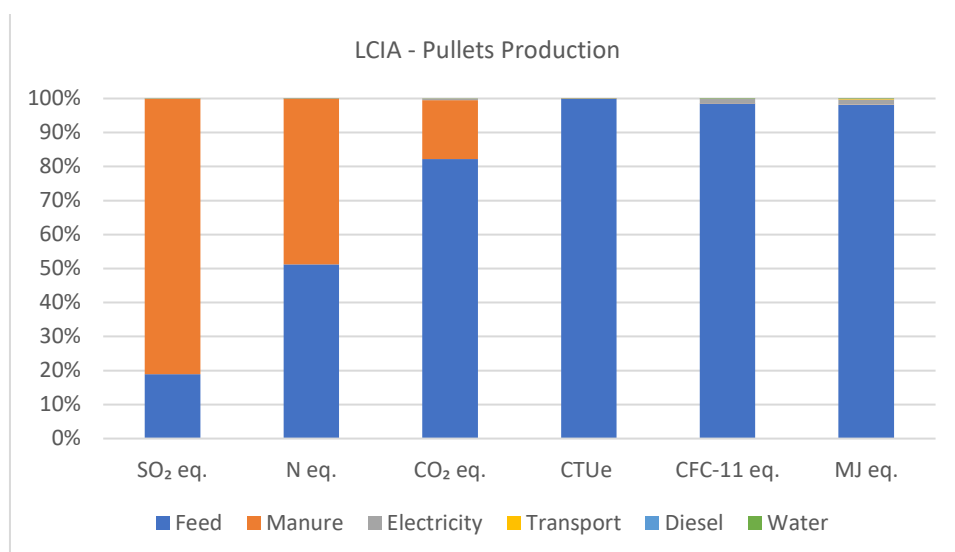


Figure 4. Acidifying emissions (kg SO₂ eq.), eutrophying emissions (kg N eq.), greenhouse gas emissions (kg CO₂ eq.), ecotoxicity (CTUe), ozone depletion (CFC-11 eq.), and fossil CED (MJ eq.) associated with the production of 1000 units of pullets produced.

3.3.3. LCIA Results—Egg Production

When analyzing the LCIA results of a ton of eggs produced, it is noted that feed inputs, manure management, and pullet production (which encompass all previously reported impacts) are the main drivers of impacts associated with egg production systems. In impact categories such as ecotoxicity, ozone depletion, and fossil CED, electricity has a greater contribution than manure management due to the nature of electricity production provided by the Brazilian utility [75].

When analyzing the LCIA results, in terms of acidifying emissions, manure management accounts for 73.8%, feed production for laying hens for 13.3%, and pullet production for 12.8%. For eutrophying emissions, manure management contributes 48.6%, feed production for laying hens contributes 36.5%, and pullet production contributes 14.9%. In terms of greenhouse gas emissions, feed production for laying hens corresponds to 62.8%, manure management to 19.3%, and pullet production to 17.4%. In terms of ecotoxicity, feed production for laying hens constitutes 80.4%, and pullet production contributes 19.5%. Ozone depletion is primarily driven by feed production for laying hens at 81.5%, pullet production at 16.7%, and electricity at 1.6%. Fossil CED is dominated by feed production for laying hens at 82.5%, pullet production at 15.4%, and electricity at 1.6% of the generated impacts. Other inputs such as transportation, diesel, and water contribute less than 1% to the impacts generated in the production of one ton of eggs. Figure 5 illustrates the percentage of impacts generated by the production of one ton of eggs.

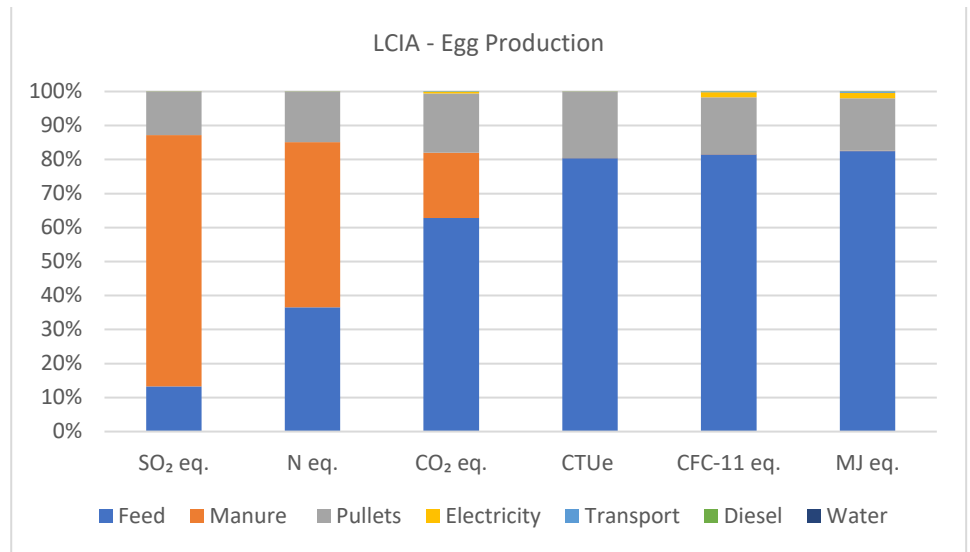


Figure 5. Acidifying emissions (kg SO₂ eq.), eutrophying emissions (kg N eq.), greenhouse gas emissions (kg CO₂ eq.), ecotoxicity (CTUe), ozone depletion (CFC-11 eq.), and fossil CED (MJ eq.) associated with the production of one ton of eggs.

3.3.4. LCIA Results—Classification Sector

When evaluating the results of the classification sector, it is possible to identify that the greatest impacts in all analyzed categories stem from egg production, consequently including the impacts of feed production, pullets, and manure management. Packaging demonstrated a higher contribution to impacts in categories related to GHG emissions (4.1%), ozone depletion (8.9%), and fossil CED (25.3%) from fossil-based plastic packaging (combs, acrylic lids, and plastic film) and cardboard boxes. Other inputs, such as electricity and water, contribute less than 1% to the impact generated in the production of one ton of classified and packaged eggs. Figure 6 illustrates the percentage of impacts generated by the production of one ton of classified eggs.

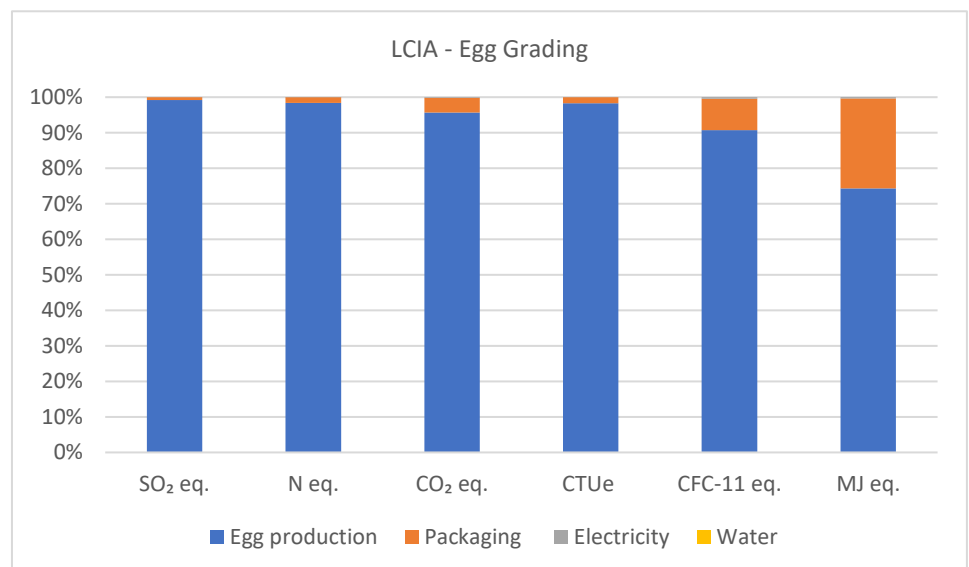


Figure 6. Acidifying emissions (kg SO₂ eq.), eutrophying emissions (kg N eq.), greenhouse gas emissions (kg CO₂ eq.), ecotoxicity (CTUe), ozone depletion (CFC-11 eq.), and fossil CED (MJ eq.) associated with the classification of one ton of eggs.

3.3.5. LCIA Results—Liquid Egg Production

In all analyzed categories, the greatest impacts stem from the egg classification sector, consequently encompassing the impacts of egg production, pullets, and feed. Considering the impacts generated by acidifying emissions, egg production accounts for 99.1%. For eutrophying emissions, egg production contributes 99.2%. In terms of greenhouse gas emissions, egg production corresponds to 92.1% and transportation to 7.1%. In terms of ecotoxicity, egg production constitutes 97.4%, with transportation contributing 2.5%. Ozone depletion is primarily driven by egg production at 82.7%, with transportation at 11.8%, gas at 3.4%, and electricity at 1.9%. Fossil CED is dominated by egg production at 70.8%, with transportation at 24.8%, gas at 2.2%, and electricity at 1.7% of the generated impacts. Other inputs, such as packaging and water, contribute less than 1% to the impacts generated in the production of one ton of liquid eggs. Figure 7 illustrates the percentage of impacts generated by the production of one ton of liquid eggs.

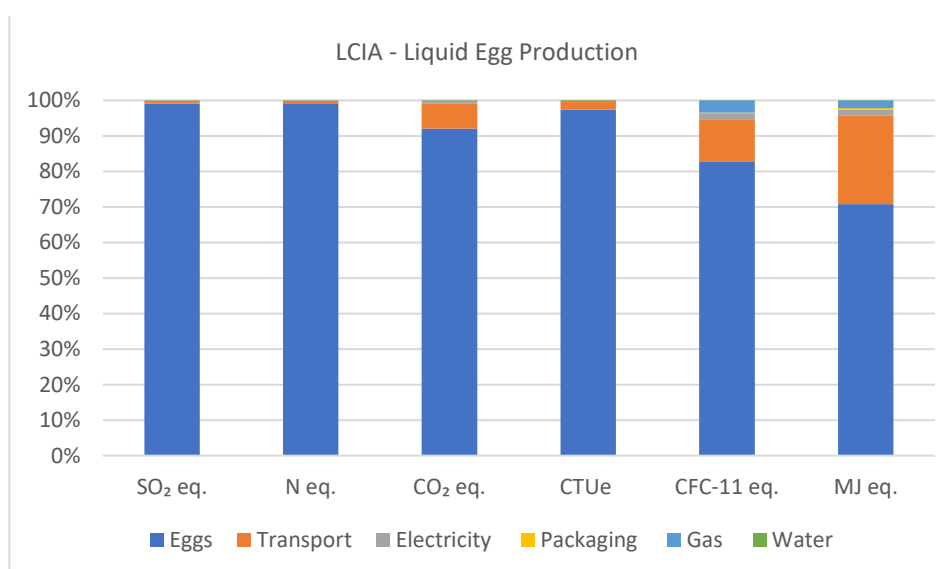


Figure 7. Acidifying emissions (kg SO₂ eq.), eutrophying emissions (kg N eq.), greenhouse gas emissions (kg CO₂ eq.), ecotoxicity (CTUe), ozone depletion (CFC-11 eq.), and fossil CED (MJ eq.) associated with the production of one ton of liquid eggs.

4. Discussion

The production of feed is directly related to the production of pullets, laying hens (eggs), and, consequently, the generation of organic compounds through the produced manure. In the United States, as reported by Pellitier et al. [28], feed production's primary impacts are attributed to animal co-products in feed composition, particularly those derived from ruminants. The composition of feed for pullets and laying hens in Brazil differs, with corn and soy identified as the major contributors to its environmental impact. In pullet feed production, a higher concentration of soy derivatives (27%), an elevated concentration of meat and bone meal (4%), and the non-adoption of corn-derived co-products (DDG) contribute to high values of greenhouse gas (GHG) emissions, ecotoxicity, and fossil CED. However, corn comprises 65% and 62% of the composition of pullet and laying hen feed, respectively. Through a comparison of these feeds, it becomes apparent that the incorporation of DDG in laying hen feed has already led to a reduction in the generated impacts. As part of an improvement plan, reconsidering the composition of pullet feeds to meet nutritional requirements

without compromising bird development could contribute to enhancing the environmental footprints of the entire production system.

In both pullet and egg production, the most substantial impacts come from feed and manure management. The regionalized supply of feed ingredients already plays a role in enhancing sustainability performance in raw material acquisition for the farm. As part of an improvement plan in manure management, promoting the development of new formulations/compositions of feeds for the pullet and laying phases can contribute to the reduction in gas emissions from intensive animal production systems. According to Hsu, Lin, and Chiou [76], high rates of crude protein can improve productive performance but may result in a significant increase in uric acid in the animals' blood plasma, leading to excess elimination through excreta. Therefore, incentivizing the creation of feed formulations that balance protein content to maintain productivity while minimizing environmental impacts could be a beneficial strategy.

Optimizing and managing the duration of the laying cycle can be a significant contributor to sustainability in production. In this study, variations in laying cycles were identified, ranging from 105 to 125 weeks, including the molting process. Future studies with a specific focus on determining the optimal balance between economic resources and environmental outcomes can be conducted to assess the efficiency of different laying cycles. This approach has the potential to offer valuable insights into achieving optimal sustainability in egg production systems.

The impacts generated from the grading sector are the same for egg production, with the additional consideration of energy expenses for egg grading and the use of packaging. As part of an improvement plan, measures related to energy efficiency and alternative packaging solutions should be considered to mitigate and minimize environmental impacts associated with the grading process. The adoption of more energy-efficient technologies and the exploration of eco-friendly packaging options can play an important role in promoting a more sustainable and environmentally friendly egg production and grading system.

The production of liquid eggs has emerged as a tool to re-utilize cracked or designated for disposal eggs, contributing to the reduction in manure. The market for liquid/processed eggs is experiencing growth both domestically and internationally. Despite incurring additional costs such as energy, transportation, and packaging, liquid egg production transforms what would be considered manure into a product that finds its way back to the consumer's table. In this assessment, the most significant impacts related to liquid egg production (excluding egg production itself) are associated with the transportation of eggs to the receiving and processing unit. The receipt of cracked eggs (Type B) may need transportation from different states due to the logistics of collecting Type B eggs from various farms throughout Brazil. As part of an improvement plan, optimizing transportation logistics and exploring energy-efficient means of transportation could be considered to minimize the environmental impacts associated with this aspect of liquid egg production.

The production of organic compost serves as an alternative for reuse and environmental control within the composting area. The farm considers organic compost production as its second-largest output and sees potential in this market, especially considering the farm's geographic location. As a result, there is an assessment of the environmental impacts generated by the composting area, which subtracts emissions resulting from the use of organic compost. This highlights that the anaerobic digestion of manure can be environmentally beneficial in other sectors of livestock farming. The overall approach aligns with sustainable practices, promoting the recycling and reuse of organic materials while minimizing environmental impacts. This commitment to sustainability

reflects a holistic perspective that embraces responsible resource management and contributes to the farm's overall environmental stewardship.

While the farm's energy use contributes partially to the environmental impacts of the egg production life cycle, there is a broad range of technologies on the market to improve energy efficiency in production. For instance, the adoption of solar panels could significantly enhance energy efficiency compared to the use of diesel generators and wood, which, in this study, introduced uncertainties in the data due to a lack of control over the quantity of wood used and the periods of use for diesel generators. Collecting detailed data on energy sources and quantities consumed in each sector would empower producers to better understand how energy use affects the sustainability of their production. Implementing more sustainable and efficient energy practices, such as the adoption of solar panels or other renewable energy sources, can play an important role in reducing the environmental footprint of egg production. This shift toward cleaner and renewable energy sources aligns with sustainable practices and contributes to the overall environmental responsibility of the farm.

4.1. Result of Data Sensitivity Analysis

The choice of impact assessment method can play an important role in estimating the environmental impacts attributed to any product or system. In order to investigate the effects of this choice, additional analyses were performed using alternative LCIA methods. The calculation of GHG emissions was considered using the IPCC 2021 and CML 2016 methods, which resulted in reductions of approximately 2.4% and 3.5% in GHG emissions, respectively, as shown in Table 12.

Table 12. GHG emissions associated with the production of 1 ton of eggs using TRACI 2.1, IPCC 2021, and CML 2016 methods.

	TRACI 2.1	IPCC 2021	CML 2016
GHG emissions (kg CO ₂ eq.)	3107.90	3033.25	2999.53
Relative %	100	97.60	96.51

Thus, the use of alternative LCIA methods may yield differences in the estimates of other generated impacts. Therefore, it is important to emphasize the significance of selecting and consistently applying a single impact assessment methodology for comparative purposes in future assessments.

4.2. Results of Data Quality and Uncertainty

At first glance, the quality of input data for most processes is generally considered high, with the exception of the evaluation of impacts associated with chick acquisition and the utilization of wood-burning generators. Nevertheless, these findings hold less significance in the context of the LCA of egg production. The data pertaining to the quantity of water, fuel, and manure generated were approximated based on the total annual information provided by the farm itself. To mitigate uncertainties in LCA models for the Brazilian egg industry, forthcoming assessments should prioritize enhancing the modeling of feed inventory, ensuring precise control over energy expenditures (energy use), and fostering the development of models to monitor and quantify resource consumption in specific sectors, such as water and fuel.

One of the primary challenges encountered is estimated to be the access limitations to data and the identified gaps in certain information during this study. Beyond the data supplied by the farm, the expansion of the national inventory database is imperative, marking a significant impediment to the

advancement of LCA due to the extensive volume of necessary data. Nonetheless, ongoing research endeavors are dedicated to the adoption and dissemination of LCA in Brazil, with a specific emphasis on consolidating the methodology and establishing a comprehensive database to bolster LCA efforts.

The second major challenge encountered pertained to the modeling of emissions from manure management systems. In this analysis, a combination of IPCC Tier 1 and 2 methods, coupled with a standardized loss rate, was employed to calculate phosphorus (P) losses. While the utilization of models is generally necessary for estimating emissions in an LCA due to measurement complexities, it is important to acknowledge that the use of models can introduce uncertainties into the proposed framework. All modeling processes for nitrogen (N), phosphorus (P), and methane (CH₄) emissions were meticulously developed and computed with the aim of directing future assessments toward the control of these emissions.

4.3. Result of Comparisons with Other Studies

Table 13 displays values related to the LCIA of battery cage egg production systems in various countries. In this study, the values correspond to 0.07 kg SO₂ eq.; 3.1 kg CO₂ eq.; 75.98 CTUe.; 2.77×10^{-5} kg CFC-11 eq.; and 10.07 MJ eq. per kilogram of eggs produced.

Table 13. LCIA considers acidifying emissions, eutrophying emissions, GHG emissions, ecotoxicity, ozone layer depletion, and fossil CED per kilogram of eggs produced in international evaluations.

Reference	Country	Acidification (kg SO ₂ eq.)	Eutrophication (kg PO ₄ eq.)	GHG (kg CO ₂ eq.)	Ecotoxicity (CTUe)	Ozone Depletion (kg CFC-11 eq.)	CED Fossil (MJ eq.)
In this study	Brazil	0.07	–	3.1	75.98	2.77×10^{-5}	10.07
Guillaume et al. [22]	Czech Republic	–	–	2.46	62.87	8.46×10^{-8}	13.33
Turner et al. [23]	Canada	0.08	0.03	2.36	–	2.30×10^{-6}	–
Estrada-González et al. [27]	Mexico	–	–	5.58	–	2.70×10^{-7}	–
Abín et al. [29]	Spain	–	–	3.50	–	–	–
Pelletier [24,25]	Canada	0.08	0.02	2.44	–	–	11.25
Pelletier et al. [28]	USA	0.07	0.02	2.10	–	–	12.30
Leinonen et al. [30,31]	United Kingdom	0.06	0.02	2.92	–	–	16.80
Wiedemann e McGahan [32]	Australia	–	–	1.4	–	–	–
Mollenhorst et al. [33]	Netherlands	0.03	0.02	3.9	–	–	–
Cederberg et al. [34]	Sweden	–	–	1.4	–	–	–
Vergé et al. [26]	Canada	–	–	2.5	–	–	–

Regarding the emission results, it is evident that acidifying and eutrophying emissions exhibit minimal variations in their outcomes. Concerning ecotoxicity and ozone depletion, the current study observed an increase of 13.11 CTUe and 2.76×10^{-5} , respectively, in comparison to the assessment conducted by Guillaume et al. [22]. Conversely, in the context of fossil CED, this study demonstrated a reduction of 6.73 in comparison to the evaluations carried out by Leinonen et al. [30,31].

The values associated with CO₂ equivalent emissions in LCIA for egg production remain consistent across all assessments, ranging from 1.4 to 5.58 kg of CO₂ eq. per kg of egg produced over the years 2006 to 2022. The battery cage production system in countries such as the Czech Republic, Canada, the USA, the UK, Australia, and Sweden exhibits lower carbon footprints than Brazilian egg

production. In contrast, Mexico, Spain, and the Netherlands show carbon footprints larger than those of Brazilian egg production. It is noteworthy that in this study, eutrophying emissions represent a value of 0.03 kg N eq. Table 14 presents values related to the LCIA of Brazilian productions, encompassing beef cattle, dairy cattle, broiler chickens, pigs, and feed for broiler chickens across various production systems.

Table 14. LCIA considers CO₂ eq. emissions in Brazilian productions of beef cattle, dairy cattle, broiler chickens, pigs, and feed for broiler chickens in their different production systems per kilogram produced.

Reference	State/Region	Product	Production System	GHG Emissions (kg CO ₂ eq./kg Produced)
Dick et al. [61]	Rio Grande do Sul	Beef cattle	Extensive and Intensive	22.52 (Live weight) and 45.05 (Carcass weight) in extensive; 9.16 (Live weight) and 18.32 (Carcass weight) in intensive.
Cardoso et al. [62]	Central-west (Cerrado)	Beef cattle (in 5 different scenarios)	Extensive and Semi-intensive	58.3(C1); 40.9(C2); 29.6(C3); 32.4(C4); 29.4(C5) (All in Carcass weight).
Willers et al. [63]	Bahia	Beef cattle	Semi-intensive	9.43 (Live weight).
Dick et al. [64]	Amazonas, Cerrado, Pampa, and Pantanal	Beef cattle	Extensive	Amazonas 13.92, Cerrado 12.10, Pampa 14.62, Pantanal 21.18 (All in live weight).
Leis et al. [65]	Paraná and Santa Catarina	Dairy cattle (ECM: energy-corrected milk)	Confined, semi-confined, and pasture	0.54 confined; 0.78 semi-confined; 0.74 pasture.
Carvalho et al. [66]	Middle Southwest region of Bahia	Dairy cattle (FPCM: fat and protein corrected milk)	Semi-intensive	1.41
Barros et al. [67]	Paraná and Minas Gerais	Dairy cattle (FPCM: fat and protein corrected milk)	Confined, semi-confined	1.14 confined in PR; 1.64 semi-confined in PR; 1.83 semi-confined in MG.
Maciel et al. [68]	Minas Gerais	Dairy cattle (with and without manure treatment by anaerobic digestion)	Semi-intensive	0.88 (with treatment); 1.16 (without treatment)
Silva et al. [69]	Central west and south of Brazil	Broilers	Intensive	2.06 (Centro oeste) 1.45 (Sul)
Lima et al. [70]	Mato Grosso do Sul	Broilers	Intensive	2.70
Alves et al. [71]	Rondônia	Broilers	Intensive	3.37
Cherubini et al. [72]	–	Swine (in 4 manure management systems)	Intensive	3.50 in tanks, 3.39 in biodigester (a), 3.11 in biodigester (b), 3.55 in composting.
Alvarenga et al. [73]	Santa Catarina	Broiler feed	–	0.75 (CW–CW) *; 0.58 (CW–SO) *; 0.68 (SO–SW) *; 0.51 (SO–SO) *.

* CW and SO represent the central-western and southern regions of Brazil, with the acquisition of maize and soybean inputs, respectively.

LCA studies for beef cattle in various production systems reveal the highest CO₂ equivalent emissions per kilogram produced, with values ranging from 9.16 to 22.52 kg CO₂ eq./kg live weight and 18.32 to 58.3 kg CO₂ eq./kg carcass weight. In some LCA studies on dairy cattle, the production system may not be specified, but the focus is on the production form, such as confined, semi-confined, and

pasture, with values ranging from 0.54 to 1.83 kg CO₂ eq./kg milk. Regarding pig LCA studies, many are dedicated to evaluating different manure management systems. In the assessment proposed by Cherubini [72], the values range from 3.11 to 3.55 kg CO₂ eq./kg live weight within the considered manure management system. In assessments related to feed production, the influence of sourcing main inputs (corn and soy) close to the feed factory is evident, varying between 0.51 and 0.75 kg CO₂ eq./kg feed.

However, when evaluating the environmental impacts of Brazilian agro-industrial productions, egg production represents impacts relatively close to the average impacts of broiler chicken and pig production.

5. Conclusions

In conducting an LCA following ISO 14044, including the cradle-to-gate farm scope and cut-off and exclusion criteria for the battery cage egg production systems and related products in Brazil, environmental impacts were quantified through emissions attributable to the intensive egg production system. Emissions related to egg production were measured at 65.06 kg SO₂ eq., 27.74 kg N eq., 3086.71 kg CO₂ eq., 75,152.66 CTUe, 2.75×10^{-5} CFC-11 eq., and 10,044.68 kg MJ eq. per ton of eggs produced. When considering egg classification, emissions slightly increased to 65.78 kg SO₂ eq., 28.26 kg N eq., 3232.93 kg CO₂ eq., 76,676.23 CTUe, 3.04×10^{-5} CFC-11 eq., and 13,541.11 kg MJ eq. per ton of eggs produced and classified. Finally, the production of processed liquid eggs in another unit of the farm resulted in emissions of 85.30 kg SO₂ eq., 36.33 kg N eq., 4355.12 kg CO₂ eq., 100,286.33 CTUe, 4.33×10^{-5} CFC-11 eq., and 18,436.53 kg MJ eq. per ton of liquid eggs produced.

When comparing battery cage egg production systems in various countries, it has been observed that countries like the Czech Republic, Canada, the USA, the United Kingdom, Australia, and Sweden demonstrate lower carbon footprints compared to Brazilian production. Conversely, Mexico, Spain, and the Netherlands exhibit higher carbon footprints. However, within the broader context of evaluating the environmental impacts of Brazilian agro-industrial productions, egg production consistently stays, on average, between the impacts associated with broiler chicken and pork production.

After a comprehensive evaluation of all impacts, it becomes evident that interventions focused on feed formulation, manure management, and the welfare of laying hens play pivotal roles in promoting sustainability within the battery cage egg production system. Managing sustainability poses both challenges and opportunities for the Brazilian egg industry. However, nutrition-related interventions, management practices (considering improved animal welfare, public health, and biodiversity loss), and the adoption of new technologies in the production system hold significant promise for achieving genuine sustainability in production.

As the first LCA of the Brazilian egg industry, considering a single Brazilian farm with high production potential, the presented results can serve as comparative benchmarks for future studies and analyses of data in different egg production systems in Brazil. These findings provide a foundation for ongoing efforts to enhance sustainability practices within the industry and offer valuable insights for stakeholders seeking to implement effective interventions for a more sustainable egg production system in the country.

Supplementary Materials: The following supporting information can be downloaded at: www.mdpi.com/xxx/s1, Table S1: Calculation of nitrogen emissions, methane, and phosphorus losses, considering the functional unit of 1000 hens produced in cages. Table S2. Calculation of nitrogen emissions, methane, and phosphorus losses, considering the functional unit of one ton of eggs produced. Table S3: Compositions of the feeds for the

Pullets houses. Table S4: Compositions of the feeds for the Laying houses. Table S5: Data quality criteria and rating system: ecoinvent pedigree matrix. Table S6: Data quality assessment: ecoinvent pedigree matrix.

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Supplementary S1

Table S1. Calculation of nitrogen emissions, methane, and phosphorus losses, considering the functional unit of 1000 hens produced in cages.

Number of hens		1025.00
Excreted N (kg)		162.06
Excreted P(kg)		33.29
Estimates of nitrogen emissions		
Description of emissions	Emission factor	Emitted N
Direct emissions of N ₂ O from manure management [(kg N ₂ O-N (kg N) ⁻¹]	0.005	1.27
Volatilization of N as NH ₃ and NO _x [(kg NH ₃ -N + NO _x -N) (kg N) ⁻¹]	0.21	34.03
Indirect emissions of N ₂ O due to NH ₃ /NO _x [(kg N ₂ O-N) (kg NH ₃ -N + NO _x -N) ⁻¹]	0.01	0.53
Leaching of NO ₃ [kg N (kg N) ⁻¹]	0.24	38.89
Indirect emissions of N ₂ O due to leaching [kg N ₂ O-N (kg N) ⁻¹]	0.011	0.67
Direct emissions of N ₂ O after application to the soil [(kg N ₂ O-N (kg N) ⁻¹]	0.01	1.61
Volatilization of N as NH ₃ and NO _x after ap. to the soil [(kg NH ₃ -N + NO _x -N) (kg N) ⁻¹]	0.21	26.89
Indirect emissions of N ₂ O due to NH ₃ /NO _x volat. [(kg N ₂ O-N) (kg NH ₃ -N + NO _x -N) ⁻¹]	0.01	0.34
Leaching of NO ₃ in the soil [kg N (kg N) ⁻¹]	0.24	29.56
Indirect emissions of N ₂ O due to leaching [kg N ₂ O-N (kg N) ⁻¹]	0.011	0.43
Total N ₂ O (kg)		4.85
Total NO ₃ (kg)		68.45
Total NH ₃ (kg)		48.92
Total NO _x (kg)		12.00
Estimates of methane emissions		
Emissions description	Emission factor	Emitted CH₄
CH ₄ (kg)	10.5	27.01
Estimates of phosphorus losses		
Emissions description	Emission factor	Emitted P
P ₂ O ₅ (kg)	0.03485	3.56

Table S2. Calculation of nitrogen emissions, methane, and phosphorus losses, considering the functional unit of one ton of eggs produced.

Number of hens		55.73
Excreted N (kg)		57.80
Lost P (kg)		11.36
Estimates of nitrogen emissions		
Emissions description	Emission factor	Emitted N
Direct emissions of N ₂ O from manure management [(kg N ₂ O-N (kg N) ⁻¹]	0.005	0.45
Volatilization of N as NH ₃ and NO _x [(kg NH ₃ -N + NO _x -N) (kg N) ⁻¹]	0.21	12.14
Indirect emissions of N ₂ O due to NH ₃ /NO _x volat. [(kg N ₂ O-N) (kg NH ₃ -N + NO _x -N) ⁻¹]	0.01	0.19
Leaching of NO ₃ [kg N (kg N) ⁻¹]	0.24	13.87
Indirect emissions of N ₂ O due to leaching [kg N ₂ O-N (kg N) ⁻¹]	0.011	0.24
Direct emissions of N ₂ O after soil application [(kg N ₂ O-N (kg N) ⁻¹]	0.01	0.75
Volatilization of N as NH ₃ and NO _x after soil application [(kg NH ₃ -N + NO _x -N) (kg N) ⁻¹]	0.21	15.78
Indirect emissions of N ₂ O due to NH ₃ /NO _x volat. [(kg N ₂ O-N) (kg NH ₃ -N + NO _x -N) ⁻¹]	0.01	0.16
Leaching of NO ₃ in the soil [kg N (kg N) ⁻¹]	0.24	18.03

Table S2. Cont.

Indirect N ₂ O emissions due to leaching [(kg N ₂ O-N (kg N) ⁻¹]	0.011	0.20
Total N ₂ O (kg)		1.99
Total NO ₃ (kg)		31.91
Total NH ₃ (kg)		22.42
Total NO _x (kg)		5.50
Estimates of methane emissions		
Emissions description	Emissions factor	Emitted CH₄
CH ₄ (kg)	10.5	3.18
Estimates of phosphorus emissions		
Emissions description	Emission factor	Emitted P
P ₂ O ₅ (kg)	0.03485	1.21

Supplementary S2

Table S3. Compositions of the feeds for the Pullets houses.

Ingredients	Pre-starter Feed	Starter Feed	Grower Feed	Maturity Feed	Pre-laying Feed
Maize	648.062	661.132	661.912	647.677	645.059
Soybean meal	240.849	206.528	196.788	176.726	194.710
Soybean hull	45.405	65.336	77.144	115.491	59.131
Limestone	6.205	9.063	12.954	12.333	51.167
Meat and Bone Meal	42.447	41.686	37.956	38.680	39.876
Methionine	3.987	3.711	2.837	1.257	2.502
Salt	3.500	3.500	3.500	3.500	3.500
Mineral and vitamin	3.000	3.000	3.000	3.000	2.000
Lysine	2.955	2.642	1.544	-	0.343
Threonine	1.376	1.117	0.961	0.036	0.223
Vitamins D	1.000	1.000	0.250	0.250	0.250
Enzymes	0.500	0.500	0.500	0.500	0.500
Organic acid	0.400	0.400	0.400	0.400	0.400
Tryptophan	0.214	0.285	0.104	-	0.239
Probiotic	0.100	0.100	0.150	0.150	0.100

Total quantity of 14,435.11 tons of feed produced for pullets in 2021.

Table S4. Compositions of the feeds for the Laying houses.

Ingredients	Starter Feed	Peak Feed	Laying Feed 1	Laying Feed 2	Laying Feed 3
Maize	602.221	622.461	626.634	633.372	624.566
Soybean meal	174.642	151.460	147.150	136.581	133.616
Limestone	93.156	94.523	102.652	108.835	106.486
DDG	80.000	80.000	80.000	80.000	80.000
Meat and Bone Meal	32.044	27.502	17.564	14.497	11.355
Soybean hull	-	9.947	15.023	15.601	24.484
Seaweed	-	-	-	-	10.000
Vegetable oil	5.349	-	-	-	-
Methionine	2.676	2.747	1.665	1.460	1.073
Sodium Sulfate	2.000	2.500	2.500	2.500	2.500
Salt	2.000	2.000	2.000	2.000	2.000
Mineral and vitamin	2.000	2.000	2.000	2.000	2.000
Lysine	1.278	1.906	0.616	0.664	0.476
Mycotoxin Adsorbent	1.000	1.000	1.000	1.000	-
Threonine	0.460	0.688	-	-	-
Choline chloride	0.500	0.500	0.500	0.500	0.500
Enzyme Bland	0.500	0.500	0.500	0.500	0.500
Tryptophan	0.174	0.266	0.196	0.240	0.194
Vitamin D	-	-	-	0.250	0.250

Total quantity of 157,267.89 tons of feed produced for laying hens in 2021.

Supplementary S3

Table S5. Data quality criteria and rating system: ecoinvent pedigree matrix.

	1	2	3	4	5
Reliability	Verified data based on measurements	Verified data partly based on assumptions or non-verified data based on measurements	Non-verified data partly based on qualified estimates	Qualified estimates (e.g. by industrial expert)	Non-qualified estimates
Completeness	Representative data from all sites relevant for the market considered, over an adequate period to even out normal fluctuations	Representative data from >50% of the sites relevant for the market considered, over an adequate period to even out normal fluctuations	Representative data from only some sites (<50%) relevant for the market considered, or >50% of sites but from shorter periods	Representative data from only one sites relevant for the market considered, or some sites but from shorter periods	Representativeness unknown or data from a small number of sites and from shorter periods
Temporal correlation	Less than 3 years of difference to the time period of the data set	Less than 6 years of difference to the time period of the data set	Less than 10 years of difference to the time period of the data set	Less than 15 years of difference to the time period of the data set	Age of data unknown or more than 15 years of difference to the time period of the data set
Geographical correlation	Data from area under study	Average data from larger area in which the area under study is included	Data from area with similar production conditions	Data from area with similar production conditions	Data from unknown or distinctly different area (North America instead of Middle East, OECD-Europe instead of Russia)
Further technological correlation	Data from enterprises processes and materials under study	Data from processes and materials under study (i.e. identical technology) but from different enterprises	Data from processes and materials under study but from different technology	Data on related processes and materials	Data on related processes on laboratory scale or from different technology

Source: Ciroth et al. [1].

Supplementary S4

Table S6. Data quality assessment:ecoinvent pedigree matrix.

Life cycle stage	Data	R	C	T	G	F
Feed Production	Feed composition	1	1	1	1	1
	Direct energy use	1	1	1	1	1
	Material and energy inputs	1	2	1	2	2
Pullet Facilities	Feed Composition	1	1	1	1	1
	Material and energy Inputs	1	1	1	1	1
	Manure management	2	3	1	2	1
	Mortalities	2	2	1	2	1
Layer Facilities	Feed Composition	1	1	1	1	1
	Material and energy Inputs	1	1	1	1	1
	Manure management	2	3	1	2	1
	Mortalities	2	2	1	2	1
Washing & Grading	Material and energy inputs	2	2	1	2	1
Egg Breaking and Further Processing	Material and energy inputs	2	2	1	2	2
Transportation	Transportation distances (foreground data)	1	1	1	1	1

The abbreviations for the columns are Reliability, Completeness, Temporal correlation, Geographical correlation, Further technical correlation as defined in the data quality scheme, according to Ciroth et al. [1].

Reference

1. Ciroth, A.; Noi, C.; Lohse, T.; Srocka, M. OpenLCA 1.10 - Comprehensive User Manual. 2020, 127. Available online: https://www.openlca.org/wp-content/uploads/2020/01/openLCA_1.10_User-Manual.pdf. (accessed on 1 March 2023)

GENERAL CONCLUSIONS

This work enabled the advancement of scientific knowledge through all the developed literature reviews. The utilization of the Life Cycle Thinking (LCT) methodology and Life Cycle Assessment (LCA) ultimately requires reviewers to consider multiple economic, social, and environmental aspects, based on rigorous approaches to life cycle thinking and assessment, and multi-objective optimization. These efforts are essential to comply with the social and environmental licenses of the sector within the regulatory, value chain, and market contexts, which, in turn, are increasingly oriented towards sustainability compliance in production systems.

Brazil is considered a productive developing country. For this reason, most of the references regarding life cycle are international, which often does not align with the Brazilian reality. Life cycle assessments of egg production developed in recent years have already been highlighting, predominantly, the relevance of the LCA methodology, and identified that chicken feed (~60%) and proper manure management (~20%) are the main contributors to greenhouse gas emissions (CO₂ eq.), among other negative environmental impacts. Furthermore, this study identified gaps in quantitative information regarding the production and impacts coming from different egg production systems (conventional and alternative) in Brazil.

Certainly, modeling emissions systems represents a significant challenge in the conduction of a LCA for a production system. In this study, a combination Tier 1 and 2 methods of IPCC was employed to estimate nitrogen (N) and methane (CH₄) emissions, while a standardized loss rate was used to calculate phosphorus (P) losses from manure management in laying hens. The utilization of models is often essential in estimating emissions for LCA, due to measurement difficulties and limited access to new technologies. However, it's important to acknowledge that the use of models introduces a level of uncertainty to the proposed model. This uncertainty should be considered and transparently communicated in the assessment to ensure the reliability and robustness of LCA results. The results obtained in this inventory served as a valuable contribution to the LCA of egg production in the intensive cage system. The conclusions of this inventory are of great importance to inform the manure management process within the LCA framework and consequently contribute to understanding the environmental impacts associated with the chicken and egg production process, where manure

management processes are considered both as final destinations and as output data (organic compost).

By conducting a life cycle assessment from the cradle to the gate of the farm, following ISO 14040 and 14044, for the intensive egg production system in cages and related products in Brazil, it was possible to quantify the environmental impacts through attributable emissions throughout the intensive egg production system. The results of emissions related to egg production were 65.06 kg SO₂ eq., 27.74 kg N eq., 3086.71 kg CO₂ eq., 75152.66 CTUe, 2.75E-05 CFC-11 eq., 10044.68 kg MJ eq. per ton of eggs produced. When considering egg classification, emissions increase to 65.78 kg SO₂ eq., 28.26 kg N eq., 3232.93 kg CO₂ eq., 76676.23 CTUe, 3.04E-05 CFC-11 eq., 13541.11 kg MJ eq. per ton of classified eggs. With the insertion of energy expenditures and packaging in the process, it can be perceived that there is a greater relevance of impacts in categories related to greenhouse gas emissions (4.1%), ozone depletion (8.9%), and fossil CED (25.3%). Finally, the production of processed liquid eggs resulted in 85.30 kg SO₂ eq., 36.33 kg N eq., 4355.12 kg CO₂ eq., 100286.33 CTUe, 4.33E-05 CFC-11 eq., 18436.53 kg MJ eq. per ton of liquid eggs. It's remarkable the increase in impacts due to the inclusion of energy expenditures in production, packaging, and also transportation to the receiving unit for liquid egg processing (in this study).

When considering the results of CO₂ eq. emissions in international life cycle assessments of egg production, the values range from 1.4 to 5.58 kg of CO₂ eq. per kg of egg produced. Countries such as the Czech Republic, Canada, USA, UK, Australia, and Sweden represent lower carbon footprints when compared to Brazilian production. Meanwhile, Mexico, Spain, and the Netherlands represent larger footprints than Brazilian egg production. When comparing the results of this study to the environmental impact values of Brazilian agro-industrial productions, egg production represents impacts relatively close to the average impacts of broiler chicken and swine production.

When evaluating the impacts arising from rearing and laying feeds, it was possible to identify that the adoption of DDG (distiller's dried grains) in laying rations has already ensured a reduction in the generated impacts. As an improvement plan, the reevaluation of the composition of rations for pullets, ensuring nutritional requirements without compromising bird development, can favor the environmental footprints of the entire production system.

In both pullet rearing and egg production, the greatest impacts stem from feed and waste management. The regionalized supply of feed inputs already contributes to sustainability performance in sourcing raw materials for the farm. As an improvement plan, incentivizing new

formulations/compositions of rations for rearing and laying phases can contribute to reducing gas emission rates arising from high crude protein levels, which are subsequently excreted.

The impacts arising from the sorting sector are similar to those of egg production, with the addition of energy expenditures for egg sorting and the use of packaging. As an improvement plan, energy efficiency measures and alternative packaging solutions should be considered. Liquid egg production has become a way to reuse cracked or discarded eggs. The market for liquid/processed eggs is growing both domestically and internationally. Despite adding energy expenditures, transportation, and packaging, among other costs, liquid egg production is promising because eggs that would otherwise be discarded become a usable product for consumers. In this assessment, the largest impact related to liquid egg production (excluding egg production) is the transportation of eggs to the receiving and processing unit. The receipt of cracked eggs (Type B) is located in another region, due to the logistics of receiving Type B eggs from other farms across Brazil.

The production of organic compost is also an alternative for reuse and environmental control in the composting area. For the farm under study, organic compost production is considered its second-largest source of income and is seen as a promising market, especially due to its geographic location near major agricultural production centers in the country, making it a large-scale absorber of organic compounds. Thus, there is a balance of environmental impacts generated by the composting area, where emissions from the use of organic compost are discounted, proving that anaerobic digestion of manure can be environmentally beneficial in other livestock sectors. As an improvement plan, a more in-depth study on controlling emissions from the composting area is needed to promote monitoring actions linked to environmental operating conditions.

Remarkably, sustainability management presents new challenges and opportunities for the Brazilian egg industry. However, interventions regarding management, nutrition, and new technologies can be extremely promising in ensuring real sustainability in production. As the first life cycle assessment of the Brazilian egg industry, the results presented here can serve as comparative parameters for future studies, as well as for data analysis in different egg production systems in Brazil. All conclusions presented here provide a database for ongoing efforts to improve sustainability practices in the Brazilian egg industry, including valuable information for stakeholders seeking to implement effective interventions for a more sustainable egg production system in the country.